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THERMIONIC SYSTEM EVALUATION TEST: YA-21U. SYSTEM TOPAZ INTERNATIONAL PROGRAM

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July 1996

Final Report

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13. Supplementary Notes

14. Abstract The primary objective of the Thermionic Systems Evaluation Test (TSET) Program was to obtain valid and sufficient information to fulfill the U.S. thermal vacuum and mechanical test requirements for space nuclear power systems. The TOPAZ-II Ya-21U System Test Plan, prepared jointly by Russian and U.S. specialists, was implemented to achieve this primary objective. A supporting objective, pursued in parallel, was to acquire valid and verifiable test results from the Russian TOPAZ-II system test program to supplement the objectives achieved during the U.S. test program.

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PREFACE

This report describes the program, system, preparations, tests, results, test equipment, and facilities related specifically to the evaluation of the Russian made TOPAZ-II Ya-21U thermionic space power system and the transfer of thermionic conversion technology to the United States. The Ya-21U system test was a significant and an integral part of the Thermionic Systems Evaluation Test (TSET) and TOPAZ International Programs (TIP).

Section 1 provides an overview of the TSET Program and a description of the Ya-21U space power system.

Section 2 describes Ya-21U's Russian heritage; the quality reviews and reports prepared during the system's first stage of manufacturing; the control and acceptance tests conducted during the second stage of manufacturing; and thermal vacuum system tests performed in the Baikal test stand at the Central Design Bureau for Machine Building, St. Petersburg, Russia.

Section 3 describes the Ya-21U test preparations. The test preparations included: (1) Delivery and inspection, documentation, readiness reviews, and test rig preparations; functional tests and modal tests: installation in the Baikal test stand thermal vacuum chamber; and preparation of TISA electrical heaters required for non-nuclear thermal vacuum testing of the system. (2) Removal of Ya-21U from the thermal vacuum chamber; calibration of mechanical test accelerometers and installation on Ya-21U's structure and critical components; transportation and installation at the mechanical test facility; and checkout of the vibration and shock equipment. (3) Removal from the mechanical test facility and return to the TSET laboratory; visual inspections, removal of accelerometers, and functional checks. (4) Reinstallation in the thermal vacuum chamber and checkout of all auxiliary systems prior to the start of final thermal vacuum performance tests.

Section 4 describes the Ya-21U test operations required to complete the transfer of Russian space power system technology to the U.S. The test operations included: modal tests of the structure, thermal vacuum performance tests, mechanical vibration and shock tests, and final thermal vacuum performance tests. The modal tests included low-level vibration of the Ya-21U structure to determine response to bending and axial and torsion excitation; determination of global modal parameters and local modes of the radiator; and collection of data for use in correlation of a finite element model of the Ya-21U structure.

The first thermal vacuum test established an operational baseline for comparison with previous Russian test results. The baseline tests included pre-startup checkouts, slow heatup and outgassing of the system, operation at steady-state, optimization of system performance, experimental tests, NaK system integrity test, rapid startups, system cool-downs, and post-test function checkout and inspection.

Several emergency shut downs and electrical shorts occurred and were corrected during the baseline tests. Post test pressure and leak checks of the cesium system revealed leaks in several TFEs. Additional thermal vacuum tests were then conducted to determine the effects of the observed leaks on the thermionic converter performance prior to the planned mechanical vibration and shock tests.

The mechanical vibration and shock tests were performed to determine the dynamic response of the Ya-21U's structure and major subassemblies to simulated launch loads and frequencies. Failure of a cesium vapor vent line and increased leak rates of TFEs were observed during post-mechanical test inspections.

Final thermal vacuum tests were conducted after the vibration and shock tests for comparison with previous test results to determine the effects of the increased cesium system and TFE leak rates on system performance.

Sections 5 presents the experimental tests and methods used, system performance data, and lessons learned during the modal, thermal vacuum, and mechanical tests of Ya-21U. The thermal vacuum system tests included optimization of work section voltage and cesium vapor pressure at different power levels and operating temperatures. Graphical presentations and evaluations of U.S. and Russian system test data were prepared to support the assessments of system, subsystem, and component performance.

Section 6 presents comparisons of U.S. and Russian operational data and results obtained during the first and final thermal vacuum performance; comparisons of U.S. and Russian mechanical test results; and assessments of the effects of increased TFE leakage. In addition, this section describes methods used to determine operating conditions and performance of individual TFEs using Ya-21U system's operational parameters.

Section 7 describes the Baikal test stand and lessons learned during operation of the test facility and support systems. This includes the vacuum systems, cesium evacuation system, voltage control and load bank, TISA heaters and electrical controls, main power supply and uninterruptable power system, test stand instrumentation, data acquisition system, and other special equipment.

ACKNOWLEDGMENT

The Thermionic Systems Evaluation Test (TSET) Program required much more than the usual resources of management and technical skills; test equipment and facilities; and operating policies, procedures, and paper to achieve its program goals and objectives. Those additional unique requirements were:

- A common vision by Americans and Russians of benefits to be derived by working side-by-side; by sharing personal skills, work ethics, and cultural values; and by each person providing his or her best-efforts to each and every task that needed to be done.
- A recognition that the TSET Program provided a first and perhaps only life-time opportunity for many Russian and American working families to know each other and remain as close friends and neighbors.
- A recollection that the time and effort contributed by each person would be a significant part of his or her life.

The following co-workers, their families and friends are acknowledged for contributing their best-efforts and sharing their lives during the TSET Program. May their futures be rewarding.

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A technical report of this size requires information to be provided from many sources by many individuals with many skills and experiences. Individuals, who were not listed above, also made many meaningful contributions to this final report. The author apologizes to those for this unintended omission.

***Note:** Dave Luchau, Dima Paramonov, Scott Wold, and Frank Wyant provided drafts of text, tables, and figures of various sections and contributed significantly to the technical scope and content of the final report.

SUMMARY

The objectives of the U.S. Thermionic Systems Evaluation Test (TSET) Program were achieved.

Valid and sufficient information was obtained during thermal vacuum and mechanical testing of the Russian TOPAZ-II Ya-21U thermionic space nuclear power system to evaluate and transfer that technology to the U.S.

The TOPAZ-II Ya-2U system represented more than 20 years of Russian space nuclear thermionic power system technology that was developed during the period from 1969 to 1990. The abundance of this technology, in the form of previously documented results from manufacturing records, assembly inspection reports, system acceptance tests, modification records, repair logs, and high temperature performance evaluations, was provided to the U.S. prior to and following delivery of TOPAZ-II Ya-21U system, ground support equipment, and the Baikal test stand to the TSET Laboratory.

After delivery of the Ya-21U system, in May 1992, test facility preparations; equipment installation and checkout; and system installation, calibration, and acceptance were successfully completed in a record time of 6 months. The joint efforts, combined skills, and active participation of Russian and U.S. specialists working side-by-side were essential ingredients for these achievements.

Ya-21U thermal vacuum system tests performed in the TSET Laboratory demonstrated and verified previous Russian test results. Ya-21U's response to thermal vacuum tests of more than 8,000 hours of system operation, severe stresses experienced during four very rapid unplanned cool-downs, and four simulated orbital startups without a single failure of a thermionic converter demonstrated that the system design is reliable and predictable.

Mechanical vibration and shock tests, performed after 5,000 hours of high temperature operation also confirmed the technology to be very durable and most robust.

In summary, the TSET Program experience, results, thermionic technology transfer, and lessons learned were significant achievements and established the baseline for development and demonstration of future thermionic space nuclear power systems. In addition, the TSET Program successfully demonstrated how former Cold War adversaries could work together efficiently, effectively, and economically; that military technology could be adapted to peaceful, non-military applications; and that meaningful, productive jobs could be provided for Russian specialists who were previously employed for military purposes.

1.0 EVALUATION TEST PROGRAM

1.1 INTRODUCTION

The primary objective of the Thermionic Systems Evaluation Test (TSET) Program was to obtain valid and sufficient information to fulfill the U.S. thermal vacuum and mechanical test requirements for space nuclear power systems. The TOPAZ-II Ya-21U System Test Plan, prepared jointly by Russian and U.S. specialists, was implemented to achieve this primary objective. A supporting objective, pursued in parallel, was to acquire valid and verifiable test results from the Russian TOPAZ-II system test program to supplement the objectives achieved during the U.S. test program (Schmidt #1).

This TOPAZ System Evaluation Test Report (1) describes the Ya-21U thermionic space power system and its Russian heritage; (2) presents results of non-prototypic evaluation tests of the Ya-21U system performed by U.S. and Russian specialists and engineers; (3) emphasizes the transfer of thermionic power system technology to the United States of America; (4) shares the lessons learned during the extended non-nuclear, high temperature operation and mechanical testing of an integrated thermionic space power system; (5) presents precautions during application of the non-prototypic test results; and (6) provides recommendations for performance testing and evaluation of future thermionic systems.

Ya-21U was the product and represented 20 years of Russian space nuclear thermionic power system technology development from 1969 to 1989. The abundance of this technology, in the form of previously documented results from manufacturing records, assembly inspection reports, system acceptance tests, modification records, repair logs, and high temperature performance evaluations, was provided by Russian Laboratories to the U.S. prior to and following delivery of six TOPAZ-II systems, ground support equipment, and the Baikal test stand to the TSET Laboratory (Voss #2 and #3).

After delivery of the first two Russian systems, V-71 and Ya-21U, in May 1992, test facility preparations; equipment installation and checkout; and system installation, calibration, and acceptance were successfully completed in a record time of 6 months. The joint efforts, combined skills, and active participation of Russian and U.S. specialists working side-by-side were essential ingredients for these achievements (Fairchild #4 and Wold #5).

Soon after its arrival, Ya-21U was designated the "Pathfinder System" because it would be used to demonstrate the design capability of the TOPAZ II systems to fulfill U.S. space power system requirements and to help build the infrastructure required to support development and demonstration of a U.S. based thermionic space power system (Schmidt #6).

The first thermal vacuum tests performed on Ya-21U prior to mechanical tests demonstrated and verified previous Russian test results. The system's response to severe stresses experienced during very rapid unplanned cool-downs, nine thermal cycles, and more than 1000 hours of system operation at temperatures above 450°C (723 K) without a significant reduction in electrical power output demonstrated the TOPAZ II design to be reliable and predictable.

Final thermal vacuum performance tests of Ya-21U, performed after 5000 hr of high temperature operation and high stress vibration and shock tests, reaffirmed the TOPAZ II system design and technology to be very durable and most robust (Luchau #7 and Siriano #8).

All together, the Pathfinder System test experience, results, thermionic technology transfer, and lessons learned were significant TSET Program achievements and established the baseline for development and demonstration of future thermionic space nuclear power systems.

1.1.1 TOPAZ International Program

The TOPAZ International Program (TIP) was a cooperative technology effort, primarily between the United States and Russia, although British and French specialists also participated in some specialized technology evaluation activities and tasks. The mission of TIP was to transfer Russian technology to U.S. laboratories and industries for non-military applications.

The TOPAZ II technology transfer and demonstration effort was initiated by the Department of Defense in December 1990 and was managed by the Ballistic Missile Defense Organization (BMDO). The U.S. participants were the Air Force Phillips Laboratory(AFPL), Sandia National Laboratories (SNL), Los Alamos National Laboratory (LANL), University of New Mexico (UNM), and the Applied Physics Laboratory (APL). The Russian participant was INERTEK, a joint venture group that included the Central Design Bureau of Machine Building (CDBMB), Russian Research Center, Kurchatov Institute, and NPO LUCH which were formerly a part of the Russian Ministry of Atomic Power.

The TSET Program combined the experience, joint efforts and resources of U.S. and Russian specialists to assure that system performance demonstrations and sufficient information could be provided to fulfill U.S. requirements for space nuclear power systems. Where possible, the TSET Program acknowledged and used valid and verifiable test results obtained from previous Russian TOPAZ II test programs to supplement that obtained during the U.S. test program.

In addition, the TSET Program successfully demonstrated how former Cold War adversaries could work together efficiently, effectively, and economically; that military technology could be adapted to peaceful, non-military applications; and that meaningful, productive jobs could be provided for Russian specialists who were previously employed for military purposes.

1.1.2 Russian TOPAZ-II Program

The Russian TOPAZ-II space reactor development program began in 1969. Twenty-six (26) systems were manufactured and 19 were tested during the period from 1970 to 1989 to assure that flight systems would provide 5 to 6 kW of electrical power for space missions lasting from 1-3 years. The basic TOPAZ-II system design remained the same, although a number of design changes were made during the development period (Voss #2).

The Russian system test program, summarized in Table 1, ended in 1989 due to economic problems. The program included 13 non-nuclear and 6 ground nuclear system tests. Four types of system tests were performed by Russians: thermal management, mechanical, electrically heated thermal vacuum, and ground nuclear. Their program confirmed that TOPAZ-II flight systems were robust, durable, and ready for launching and orbital operation with Russian spacecraft (Voss #3).

When Russia offered to sell, the U.S. seized the opportunity to buy TOPAZ-II systems for evaluation and demonstration of their thermionic reactor technology. In May 1992, two C-5A military transports delivered the V-71 and Ya-21U systems, the complete Baikal test stand, and numerous Russian documents to Albuquerque, NM.

Table 1. Summary of Russian system test program.

System	TFEs	Life-Yr.	Year	Test-Hr	Description of Tests
V-11	3	1	71/72	3200	Development of test methods and operation.
V-12	31	1	72/73	850	Development of pre-launch technology & operations.
V-13	31	1	72/73	-----	Transportation, shock, dynamic, & cold testing.
Y-20	31	1	72/74	2500	Neutron characteristic, radiation fields, & zero power.
Ya-21	31	1	------	-----	Neutron characteristic, radiation fields, & pre-launch.
Ya-22	31	1	------	-----	Not assembled.
V-15	31	1-1.5	80/80	-----	Cold tests - Used 2nd generation TFEs
V-16	31	1-1.5	75/79	2300	Transportation, shock, vibration & electrical tests.
Ya-23	31	1-1.5	75/76	5000	Fuel loading, radiation & nuclear safety - steady state.
E-31	31	1-1.5	76/78	4600	Nuclear ground test, ACS startup & steady state.
Ya-24	31	1-1.5	78/81	14000	Steady state system testing with 2nd generation TFEs.
E-32	31	1-1.5	------	--------	Used as mockup for transport & handling procedures.
Ya-25	31	1-1.5	------	--------	Used as mockup with spacecraft.
E-35	31	1-1.5	------	--------	Used for experiments in Baikal test stand.
Ya-26	31	1-1.5	------	--------	Damaged during fabrication & not tested.
V-71	37	1.5	81/87	1300	Mechanical, cold test, zero power critical, electric tests.
Ya-81	37	1.5	80/83	12500	Nuclear ground tests & steady state operation.
Ya-82	37	1.5	83/84	8300	Nuclear ground test, ACS startup & LOCA.
E-37	37	1.5	84/86	-------	Zero power critical, static & torsion tests.
E-38	37	1.5	86/86	4700	Nuclear, pre-launch, ACS startup, & steady state tests.
E-39	37	1.5	------	-------	Changed reactor-changed system identification to E-41.
E-40	37	1.5	88/88	-------	Cold testing with thermal cover.
E-41	37	1.5	88/88	-------	Mechanical & leak tests, & changed radiation shield.
E-42	37	1.5	88/88	-------	Welding error in fabrication - system not to be used.
Ya-21U	37	3.0	87/89	2500	Used modified TFEs & performed electric tests.
E-43	37	3.0	88/88	-------	Flight unit-has not been tested.
E-44	37	3.0	-------	-------	Flight unit-has not been tested.
E-45	37	3.0	-------	-------	Flight unit-assembly not completed.

1.2 TSET GOAL AND OBJECTIVES

The TSET goal was to test TOPAZ-II reactor systems as closely as possible to the guidelines provided by MIL-STD-1540B. The primary objective was to obtain sufficient and valid information to fulfill U.S. thermal vacuum and mechanical qualification test requirements for space nuclear power systems. This objective was pursued by acquiring verifiable test results

obtained from previous Russian system tests to supplement results obtained during the U.S. TSET Program. Specific non-nuclear system tests were performed by TSET and enabled comparison of U.S. test results with those obtained previously by Russian specialists.

The test program, illustrated by Figure 1, was prepared with Russian participation. Guidance during preparation of the test program was provided by MIL-STD-1540B, DoD-HDBK-343, and QA Program Implementation Guide (DOE 5700.6C).

1.3 TOPAZ-II SYSTEM EVALUATION TEST PROGRAM

The original U.S. TOPAZ-II system test program required specific tests to be performed on each of six available systems. Information and technology obtained from initial system tests would be applied directly to future system tests. Ya-21U was designated the "Pathfinder System" because it had been manufactured and assembled into one integrated system using the latest Russian design features and components.

As such, thermal vacuum and mechanical testing of Ya-21U provided the best opportunity for overall evaluation of Russian space power technology with the least expenditure of resources in the shortest period of time.

1.4 REVISED YA-21U TEST PLAN

The original Ya-21U test plan was revised and shortened after plans to demonstrate an integrated nuclear electric propulsion system and spacecraft in space were eliminated. The revised Ya-21U test plan included a modal test, thermal vacuum baseline performance test, vibration and shock tests, and final thermal vacuum system performance tests. The planned tests would begin at low stress levels and end at high stress levels to permit comprehensive evaluations of system's performance and durability. Table 2 lists the revised planned sequence of system tests and test levels.

1.5 COMPLETED YA-21U SYSTEM TESTS

The actual tests performed on Ya-21U included: a modal test, eight thermal vacuum performance tests, a set of mechanical vibration and shock tests, and five final, post-mechanical thermal vacuum system performance tests. The actual tests performed on Ya-21U accommodated unanticipated problems encountered with the TSET facility's uninterruptable power supply system and the Baikal test stand equipment and permitted more comprehensive evaluations of system's performance and durability. Table 3 lists the sequence, dates, test duration, input power level, and description of the actual Ya-21U tests that are reported in Sections 3, 4, 5, and 6 of this report.

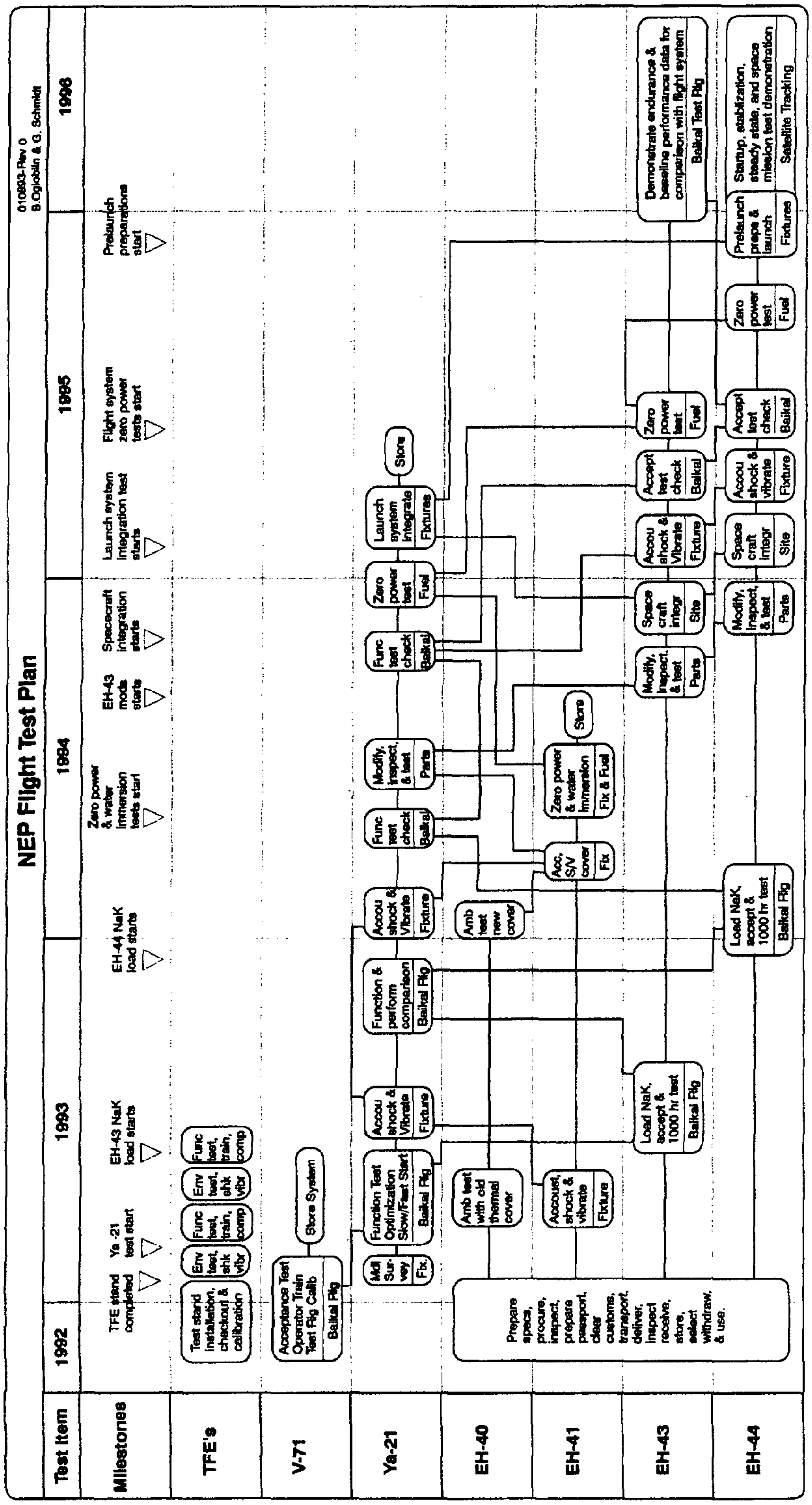


Figure 1. U.S. TOPAZ-II Thermionic Systems Evaluation Test Program.

1.6 SYSTEM DESCRIPTION

The Ya-21U system, illustrated by Figure 2, was a compact space nuclear power system based on thermionic power conversion. Major functional subsystems of the TOPAZ-II system included: (1) a nuclear reactor that contained the enriched fuel, moderator and thermionic converters; (2) a radiation shield; (3) a NaK coolant system; (4) a cesium supply system; (5) gas supply systems; (6) a startup unit and battery; (7) support structures; (8) instrumentation sensors; (9) a reactor control and monitoring system; (10) an automatic control system; and (11) a segmented thermal cover (Stepennov #9). The system flow diagram with ground test interface connections is illustrated by Figure 3 and the system block diagram is illustrated by Figure 4.

Table 2. Planned Ya-21U mechanical and thermal vacuum test sequence.

System Test	Test Purpose	Test Level
Modal	Determine modal response	Shaker force level < 10 lb at a band with of 3-64 Hz
1st Thermal vacuum	Determine baseline system performance at design operating levels.	Thermal power range: 75 to 95 kWe Work section voltage range: 15 to 30 V Cesium pressure range: 0.4 to 2.0 torr Vacuum chamber pressure: $<5.0 \times 10^{-5}$ torr Duration of test: ~1000 hr
Mechanical Vibration	Determine response of structure to sine vibration during 1 minute sweep per axis at acceptance level.	5 Hz at 0.5 g 5 - 8 Hz at < 1.0 g (actual level selected during test) 8 - 40 Hz at 1.0 g 40 - 100 Hz at 0.9 g 100 - 200 Hz at 0.8 g
Mechanical Vibration	Determine response of structure to random vibration during 1 minute sweep per axis at acceptance level.	20 - 70 Hz at 0.02 g^2/ Hz 70 - 100 Hz (actual level selected during test) 100 - 800 Hz at 0.06 g^2/ Hz 800 - 2,000 Hz (actual level selected during test) 2,000 Hz - 0.013 g^2/ Hz
Mechanical Shock	Determine response of structure to axial and lateral shock loads at acceptance level.	Axial: 50 Hz at 200 g 50 - 1,000 Hz (actual level selected during test) 1000 - 10,000 Hz at 3,500 g Lateral: 50 Hz at 200 g 50 - 1,000 Hz (actual level selected during test) 1000 - 10,000 Hz at 6,000 g
2nd Thermal vacuum test	Determine variance in system performance at design operating levels due to acceptance mechanical test stresses.	Thermal power range: 75 to 95 kWe Work section voltage range: 15 to 30 V Cesium pressure range: 0.4 to 2.0 torr Vacuum chamber pressure: $<5.0 \times 10^{-5}$ torr Duration of test: ~1000 hr

Table 3. Actual Ya-21U system tests performed in U.S.

Test No.	Dates	Test Time (hr)	Input Power (kW)	Test Description
0	08/93	--	--	Modal tests
1	08/31/93 - 10/16/93	1097	95	Steady-state performance tests
2	11/29/93 - 12/02/93	58	51	Emergency shutdown
3	12/10/93 - 12/21/93	243	95	Power optimizations
4	03/07/94 - 03/09/94	43	90	Emergency shutdown
5	03/12/94 - 03/13/94	23	81	Emergency shutdown
6	04/11/94 - 04/22/94	250	95	Power optimizations - no thermal shield
7	08/01/94 - 08/07/94	143	95	Power optimizations
8	08/11/94 - 08/17/94	133	95	Power optimizations
	09/94	--	--	Mechanical vibration and shock tests
9	10/20/94 - 11/14/94	602	95	Power optimizations
10	11/14/94 - 11/19/94	111	105	Rapid startup and power optimizations
11	12/06/94 - 12/14/94	199	105	Rapid startup and power optimizations
12	02/15/95 - 02/28/95	164	105	Steady-state tests with cesium leaks
13	02/28/95 - 03/31/95	615	105	Rapid startup and steady-state tests with TFE leaks
	08/93 - 03/95	3681		

The reactor was designed to provide 115-135 kWe of thermal energy to 37 thermionic converter fuel elements (TFEs) during ground nuclear tests and planned flight demonstration tests. At this power level, the TFE work section would provide 5-6 kWe at 28-30 VDC at the beginning of a 3-5 year life.

NOTE: During non-nuclear TSET demonstration tests and acceptance and performance evaluations, electrical tungsten heaters (TISAs) were inserted into the nuclear fuel cavities of the TFEs and used to heat the Ya-21U system. Approximately 88 % of the TISA thermal energy was provided directly to the 37 TFEs. The remaining 12 % was lost before reaching the TFE fuel cavities. At a TISA heater power input of ~95 kW, the thermionic converter work section received ~77 kW and provided 2.6-2.9 kWe to the spacecraft interface at 28-30 VDC.

Ya-21U had a truncated conical exterior ~3.9 m in height with a base-plane diameter of ~1.4 m and a reactor assembly diameter at the top of ~0.4 m. The system weighed ~1060 kg.

1.6.1 Nuclear Reactor

The nuclear reactor was a major assembly of the TOPAZ-II space power system. It was located at the top of the conical-shaped system, had an overall height of 0.920 m and a diameter of 0.408 m including the radial beryllium reflectors that surrounded the reactor core vessel. The compact reactor was moderated by zirconium hydride and had thermionic converters built into the reactor moderator blocks within the reactor core. The highly enriched nuclear fuel was located in the inside cavity of the thermionic converter cathodes and could be inserted or removed to accommodate non-nuclear acceptance tests and transportation to other facilities.

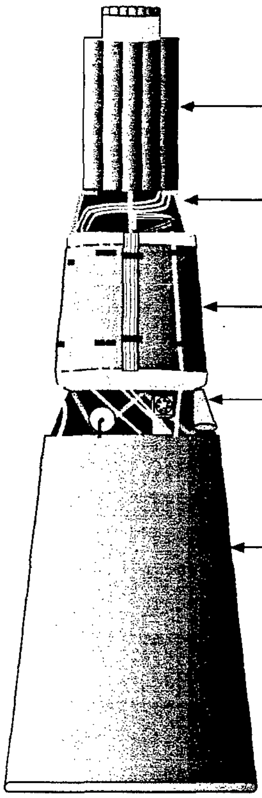


Figure 2. TOPAZ-II space nuclear power system.

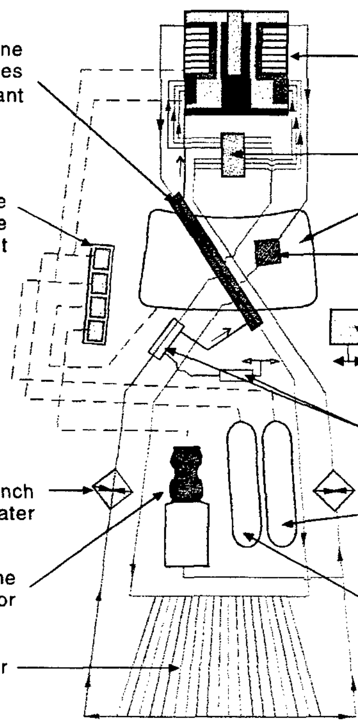
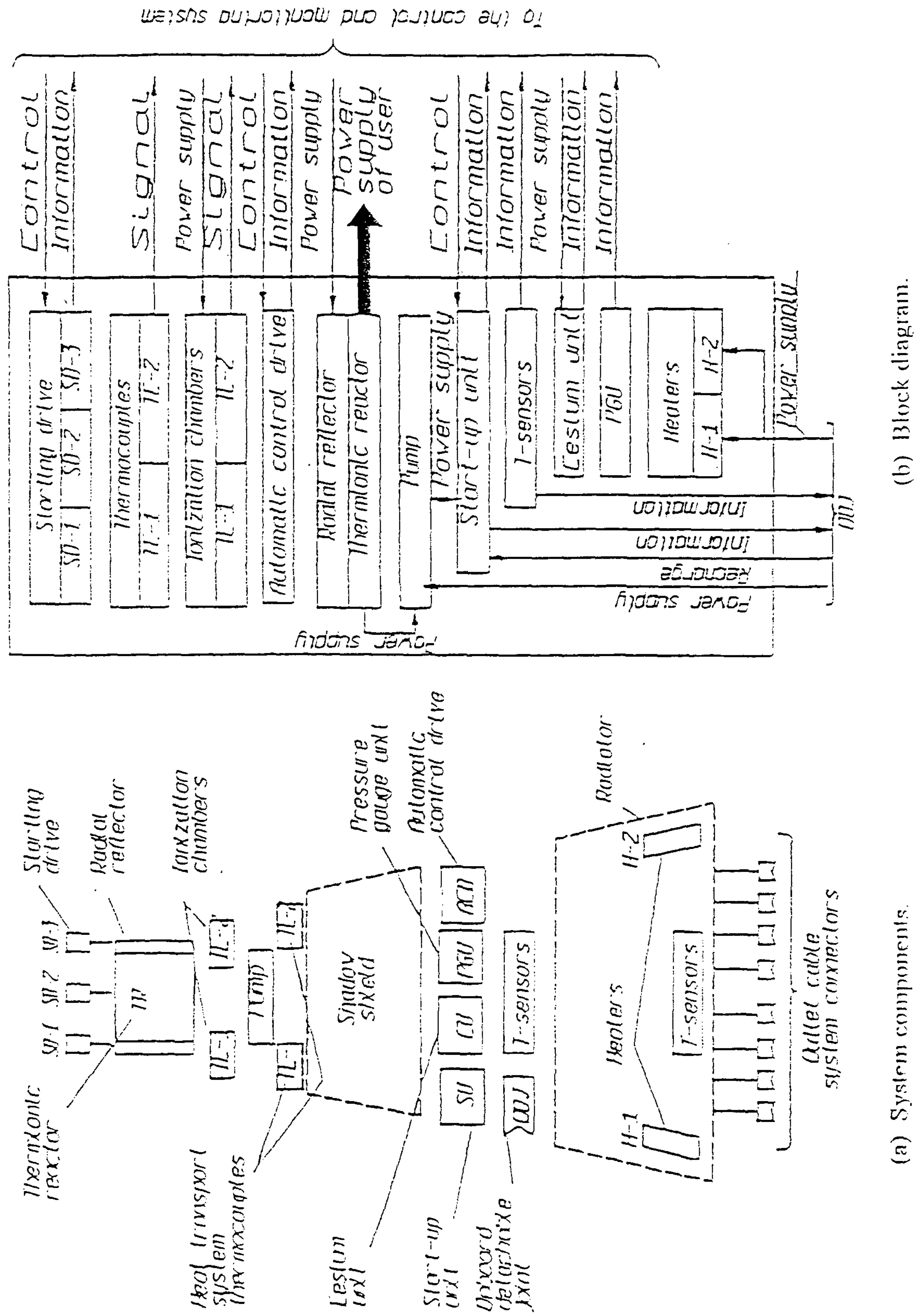


Figure 3. TOPAZ-II schematic flow diagram.



(b) Block diagram.

(a) System components.

Figure 4. TOPAZ-II block diagram.

The nuclear reactor contained 37 single-cell TFEs fueled by enriched uranium dioxide (UO_2) fuel pellets, as illustrated by Figure 5. The work section of the converter contained 34 TFEs that provided power to operate the reactor and spacecraft payloads. The pump section contained three TFEs that provided electrical power for the electromagnetic (EM) pump. A top cross-section view of the reactor is illustrated by Figure 6 and its principal parameters are summarized in Table 4.

The design of the single cell TFE, illustrated by Figure 7, permitted fuel loading from the top of the TFEs after system construction and non-nuclear testing of the entire power system. This feature permitted transportation of the highly enriched uranium oxide fuel in separate containers from the space power system and enabled final fuel loading to be performed just before ground nuclear testing or launch. The TFEs were located within channels of the ZrH moderator blocks, which were canned in stainless steel (El-Genk #10).

Radial and axial beryllium (Be) reflector segments surrounded the reactor core, as illustrated by Figure 8. The radial reflector contained three safety and nine control drums. Each drum contained a section of boron carbide (B_4C) neutron poison that assured control of the nuclear reaction during drum rotation and system startup.

Escaping fission neutrons produced within the reactor core were reflected back into the core and fuel by the control drums. The reactor power could be increased, maintained at a constant level, or decreased by increasing or decreasing the quantity of neutrons reflected back into the reactor core or permitted to escape into space. During nuclear operation, the TFE emitters were heated by nuclear fuel to temperatures between 1527 and 1827°C (1800 and 2100 K). Waste heat was removed from the outer surfaces of the TFE collectors by pumped NaK coolant which maintained the collector temperature during operation.

Table 4. TOPAZ-II reactor parameters.

Reactor core diameter	0.260 m
Reactor core height	0.375 m
Reactor diameter	0.408 m
Reactor height (overall)	0.920 m
Reactor core fuel loading	27 kg
Reactor mass	290 kg
Neutron spectrum	Epithermal
Fuel and enrichment	UO_2 / 96%
Reactor structural material	Stainless steel
Moderator block diameter	0.260 m
Moderator block height (5 required)	0.055 m
Axial beryllium reflector diameter/height	0.260/0.055 m
Radial beryllium reflector diameter/height	0.067/0.480 m
Number of safety drums	3
Number of control drums	9

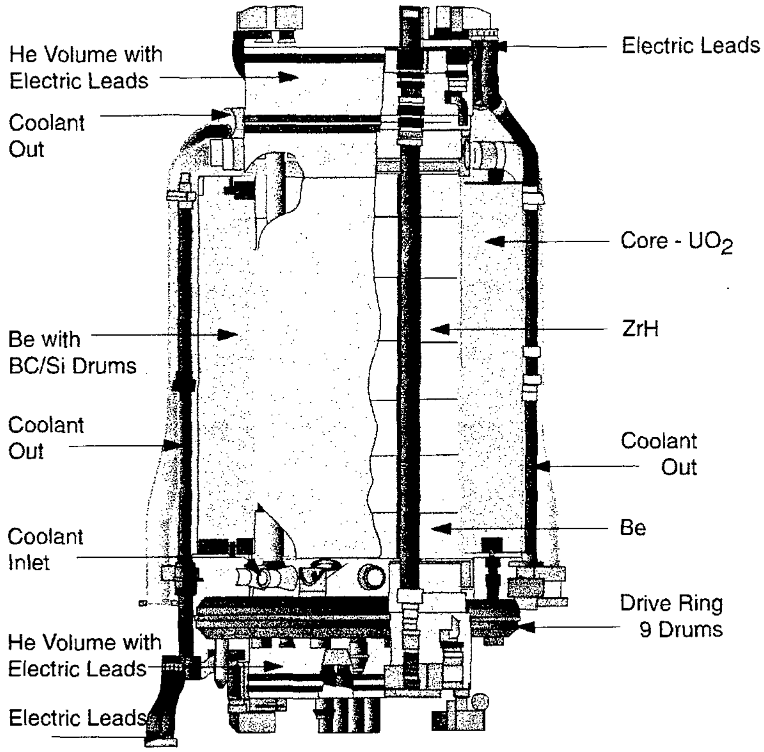


Figure 5. TOPAZ-II nuclear reactor.

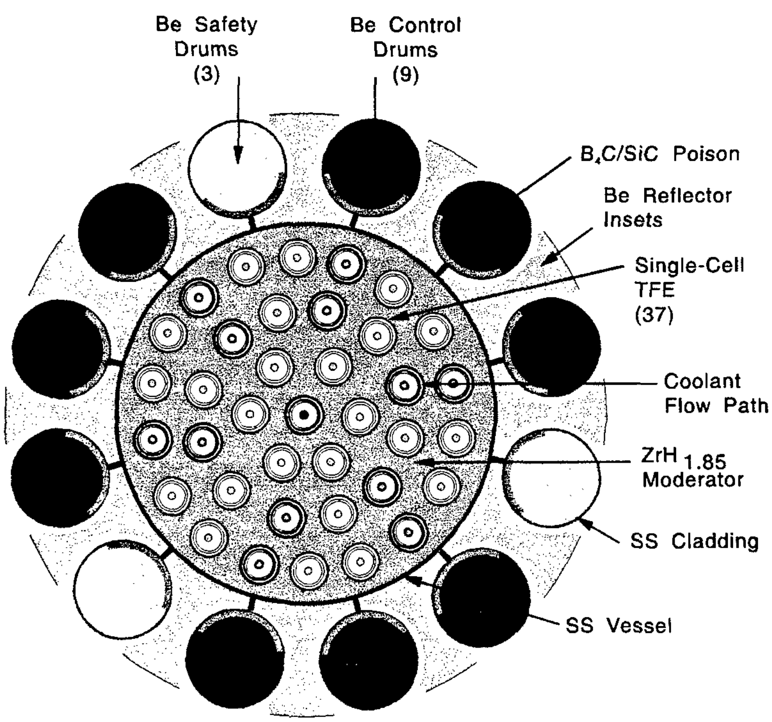


Figure 6. Top cross-section view of TOPAZ-II reactor.

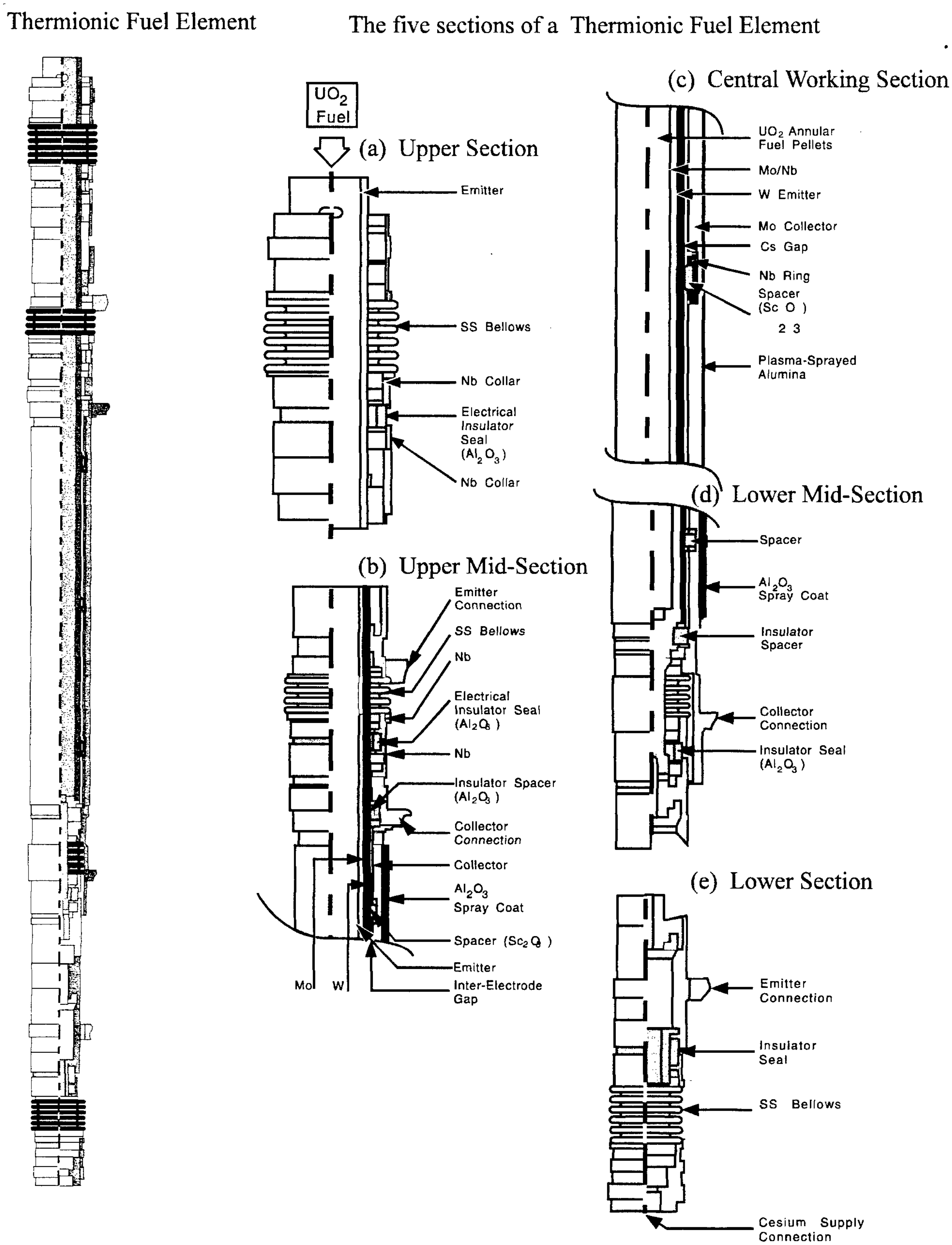
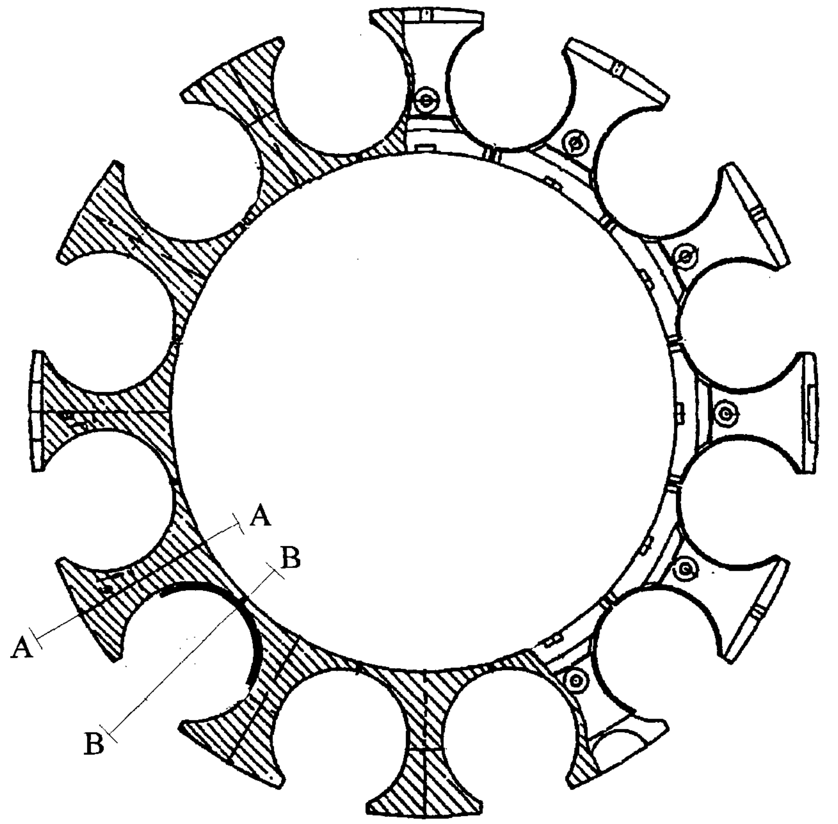
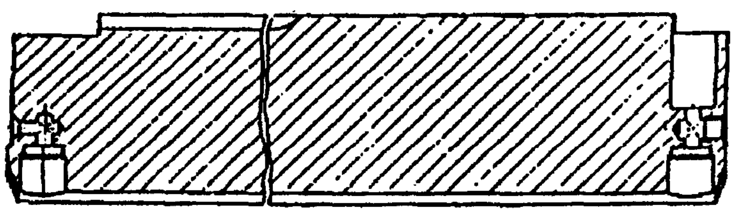


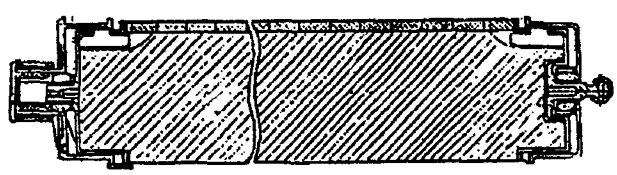
Figure 7. TOPAZ-II thermionic fuel element and detailed sections.



(a) Top view.



(b) Cut away view, A-A.



(c) Control rod, B-B.

Figure 8. TOPAZ-II beryllium reflectors.

1.6.2 Radiation Shield

The lithium hydride (LiH) neutron radiation shield, illustrated by Figure 9, was attached to the lower end of the reactor. The stainless steel container for the LiH provided gamma shielding and structural support between the reactor and main structure. The radiation shield was designed to reduce the radiation dose after 3 years of operation to 10^{11} neutrons/cm^2 and 0.05 Mrad gamma at 18.5 m from the center of the reactor core.

The radiation shield was secured to the main support structure or frame and provided structural mounting and support for the reactor assembly, EM pump, startup unit and battery, pressure transducers, control drive actuator motor, power cables, and buses.

1.6.3 NaK Coolant System

The NaK coolant system was comprised of the EM pump, piping, gas absorber hot trap, radiator, volume compensator, and two wrap-around heaters. A schematic of the NaK coolant system is shown in Figure 3.

The coolant system contained approximately 21 liters of eutectic NaK liquid metal. The eutectic NaK coolant (22 % sodium and 78 % potassium) was circulated through the stainless steel heat rejection system at a flow rate of 1.5 kg/s by a direct current conduction EM pump. The eutectic mixture had a freezing temperature of ~ -12°C (261 K).

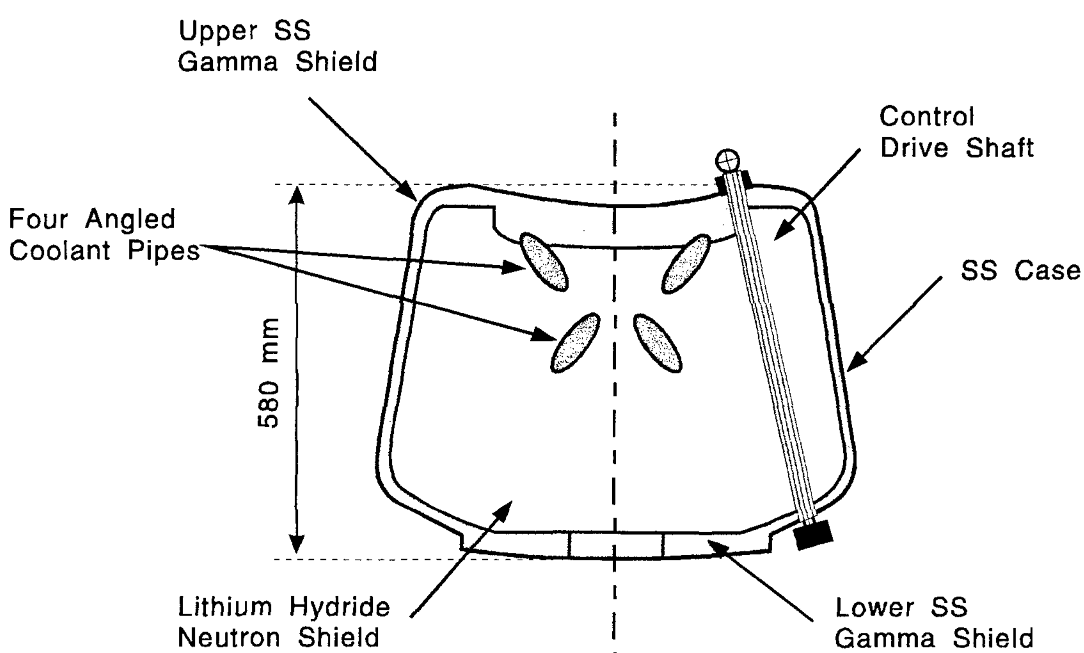


Figure 9. TOPAZ-II radiation shield.

The EM pump, illustrated by Figure 10, was located between the radiation shield and the bottom of the reactor and required 1050 A of current at 0.45 V during rated operation. During reactor startup in orbit, the startup unit was designed to supply 600 A to the EM pump, which provided a coolant flow rate of 0.75 kg/s (El-Genk #11).

The cold NaK coolant flowed from the lower radiator manifold through the radiation shield to the pump and then to the lower inlet plenum of the reactor core. The coolant then flowed through the core, exited the upper plenum through two outlet pipes, flowed through the radiation shield, and entered the upper radiator manifold. A gas absorber (hot trap) was located within one of the outlet pipes that passed through the radiation shield.

The truncated conical radiator, illustrated by Figure 11, had a height of ~1.83 m, upper and lower diameters of 0.824 and 1.346 m and a surface area of 7.2 m^2. The radiator, when filled with NaK, weighed ~50 kg and contains 78 copper-finned, stainless steel tubes connected to the upper and lower manifolds for rejection of waste heat to space.

Located within the conical radiator were the NaK volume compensator and two gas supply bottles. The volume compensator, illustrated by Figure 12, was connected to one of the NaK coolant return pipes. Two electrical resistance heaters were wrapped around the two NaK coolant return pipes to permit heating and maintenance of the NaK coolant temperature during pre-launch operations.

1.6.4 Cesium Supply System

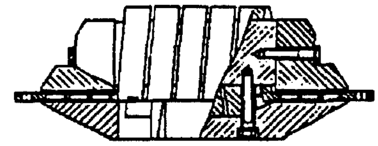
The interelectrode gaps of the TFEs are supplied with pressure-regulated cesium vapor by the cesium supply system to improve the conversion efficiency of the TFEs.

The cesium supply system includes the cesium vapor source (reservoir and pressure regulator), a vapor supply line, heat exchanger, vapor plenum, and two vents to space, as illustrated by the schematic diagram, Figure 13. The single cesium source, described by the technical information in Table 5 and illustrated by Figure 14, is the major and most important component of the cesium supply system (Luppov #12).

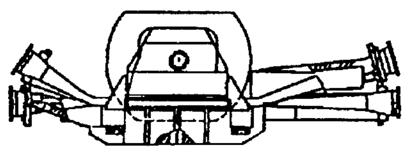
The cesium source is heated by NaK coolant returning to the reactor and the cesium vapor supply line is heated by NaK from the reactor. Approximately 0.5 g/day of cesium vapor and other gases are vented from the cesium supply system through orifices to space during normal operation of the TOPAZ II space power systems.

Within the cesium source is a thermal wick that controls the flow of cooled cesium liquid from the cesium reservoir to the pressure regulation chamber. The cesium liquid is prevented from vaporization before reaching the pressure regulation chamber by transfer of heat from the thermal wick to a small space radiator that is connected thermally to the wick.

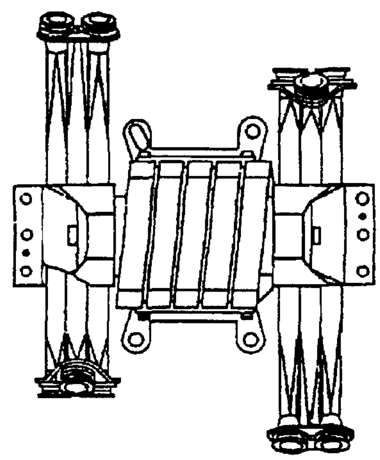
Cesium vapor produced within the cesium source during system startup in space is released to the cesium plenum and TFEs when the TFEs produce 30-50 A of current. This current actuates a valve in the cesium source that punctures a diaphragm which vents helium gas from the cesium supply system and TFE interelectrode gaps and permits diffusion of the cesium vapor to the TFE plenum.



b) Interior side view

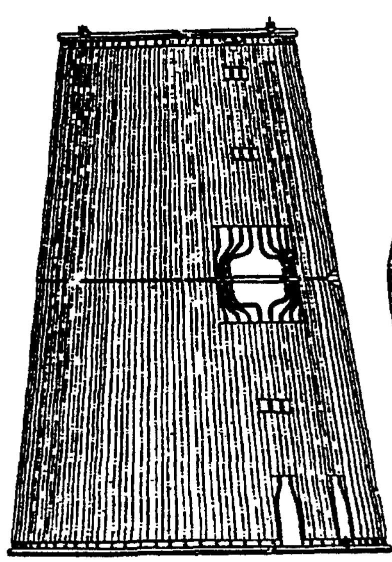


a) Front view

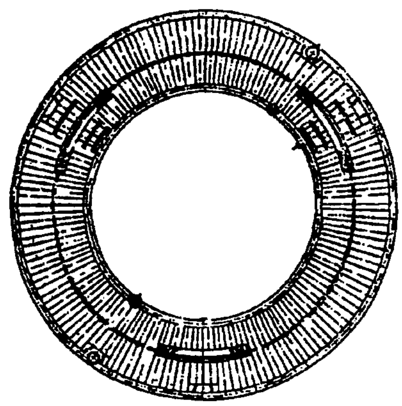


c) Top view

Figure 10. TOPAZ-II EM pump.



a) Side view



b) Top view

Figure 11. TOPAZ-II radiator

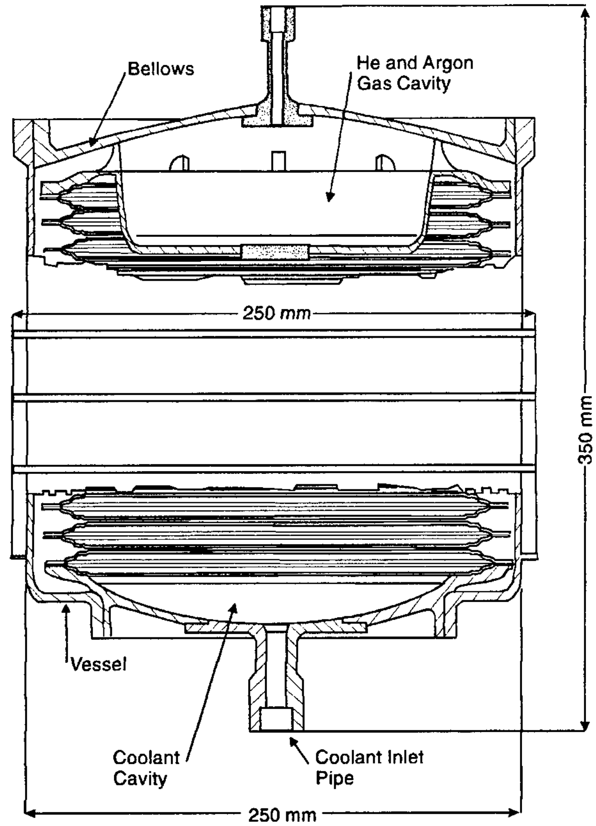


Figure 12. TOPAZ-II volume compensator

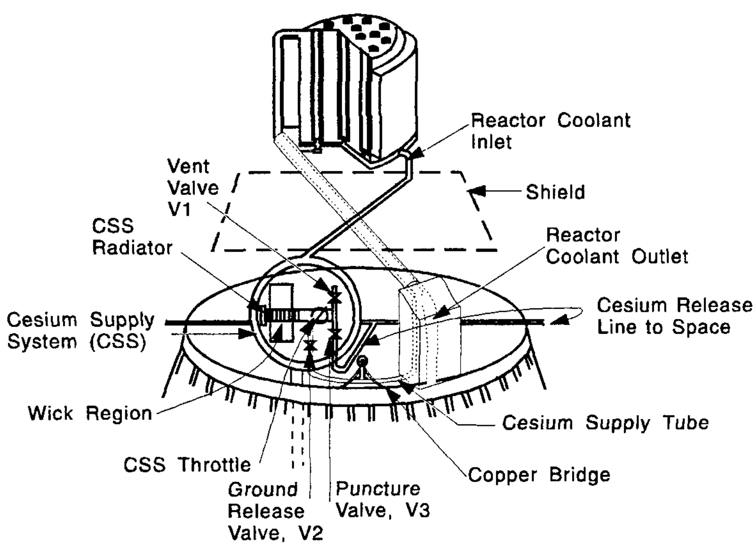


Figure 13. TOPAZ-II cesium system schematic diagram.

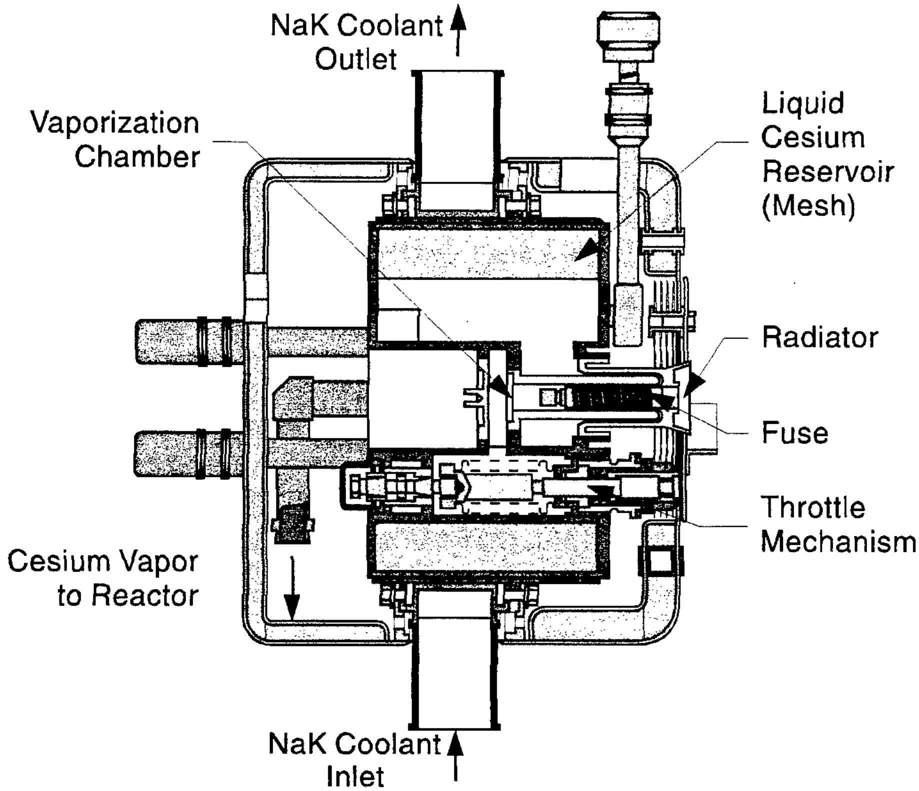


Figure 14. TOPAZ-II cesium reservoir and regulator.

Table 5. Technical data description of cesium source.

Parameter	Value
Operating temperature in steady-state mode (°C)	400 - 500
Cesium consumption (g/day)	0.5 ±0.2
Range of cesium vapor pressures for system tests (torr)	0.4-4.0
Accuracy of cesium pressure setting in steady-state mode (%)	±10
Maximum permissible operating temperature range (°C)	350 - 550
Time to reach nominal working cesium pressure (min)	70
Automatic valve actuation current (A)	30 - 50
Automatic valve actuation time (s)	~ 2
Filled cesium mass (g)	1000 ±50
Mass of cesium source in filled condition (kg)	15
Operating life (yr)	3.0
Cesium purity (% Cs)	99.9990

Note: During thermal vacuum acceptance tests of the cesium source, cesium pressures were determined for specific throttle valve positions from fully closed to fully open. The relationship between the number of turns of the throttle valve actuator and the corresponding cesium pressure was provided with each cesium source, as indicated by Figure 15. This calibration of the cesium throttle valve was used to determine the optimum cesium pressure during acceptance tests of the integrated space power system.

Cesium pressures could be varied by the calibrated throttle valve between 0.1 and ~5.0 torr. However, the normal range during system testing was between 0.4 and 2.0 torr at reactor inlet temperatures between 352 and 552°C (625 and 825 K). During system acceptance tests and performance evaluations, a remote operator located outside the vacuum test chamber was connected to the throttle valve on the cesium source. This permitted adjustment and optimization of the cesium pressure over a wide range of system power levels, temperatures, and resistive loads during system testing (Schmidt #13).

Four design features were incorporated in the cesium source and contributed to its simple, trouble-free, and predictable performance during system operation. First, waste heat from the TFEs was used to heat the cesium source, produce the cesium vapor, and maintain cesium vapor temperatures required by the TFEs from system startup to shutdown. No electrical power was required to maintain, monitor, or manage the cesium supply system. This feature eliminated the need for electrical heaters, temperature sensors, and temperature controls during thermal vacuum testing, pre-launch preparations, launch to orbit injection, orbital startup, operation at full power, and system shutdown (Sinyutin #14).

Second, the cesium reservoir stored, maintained, and provided a constant supply of high purity cesium over a wide range of operating temperatures, after high vibration and shock stress levels, and during zero gravity operation of the space power system. This feature permitted the cesium reservoir to be charged during component acceptance and calibration testing; hermetically sealed and stored until final system assembly; and to be easily connected to evacuation test rigs during system thermal vacuum qualification or acceptance tests.

Third, the cesium wick supplied a very small volume of cesium at a very low and consistent flow rate, over a wide range of operating temperatures, after numerous thermal cycles, high vibration and shock stress levels, and extended operating periods.

The very small cesium wick, illustrated by Figure 16, included four main parts: (1) a core ~8 mm outside diameter and 40 mm in length; (2) a wire coil ~31 mm in length that surrounded the core. The wire coil was made from a wire that was 0.2 mm in diameter and ~4,772 mm in length; (3) a bushing ~10 mm outside diameter and ~50 mm in length that surrounded the wire coil; and (4) a radiator ~40 mm in length that surrounded the bushing.

The empty space between the coils of wire, bushing, and core formed two parallel fluid channels or capillaries ~4,772 mm in length with each having a cross-sectional area of ~0.0043 mm^2. The liquid cesium flowed from the reservoir to the cesium vapor plenum inside the cesium source through these two fluid channels. During system power operation, the average cesium fluid velocity within each of the fluid channels was ~1,400 mm/hr. At this average fluid velocity, ~3.4 hr was required for liquid cesium at a temperature of 250°C (523 K) to flow through the 31 mm long coil or wick.

And fourth, the cesium vapor throttle valve, illustrated by Figure 17, included three major components: (1) two spiral grooved variable orifices that were connected in series; (2) a hermetically sealed actuator to permit adjustments; and (3) a throttle body that contained and supported the variable orifices and sealed actuator.

The throttle valve provided stable, repeatable, reliable, and convenient adjustment of cesium pressures over a wide range of system operating temperatures, power levels, and extended operating periods. This design feature was most significant because final adjustments and optimization of the cesium pressure could be made <u>after conditioning and evaluation</u> of the thermionic converter while the cesium subsystem was operating at the designed performance levels during integrated system acceptance tests (Schmidt #15).

The unique feature of the throttle valve was the use of spiral grooved variable orifices that were cut into the two solid cylinders that were each 8 mm in diameter and 8 mm in length. The "V" shaped spiral groove had an included angle of 60 degrees, a pitch of 1.5 mm, and a length of ~134 mm. The groove depth varied from 0.546 mm at the inlet end to 0.922 mm at its outlet.

During extended steady-state nuclear operation in space, the cesium source also permitted diffusion and release of helium, hydrogen, oxygen, and other gases from the cesium system. These gases may accumulate within the TFEs and cesium supply system during operation and cause degradation of their performance. This design feature improves prediction of the end-of-life performance of single cell thermionic converter space reactor power systems.

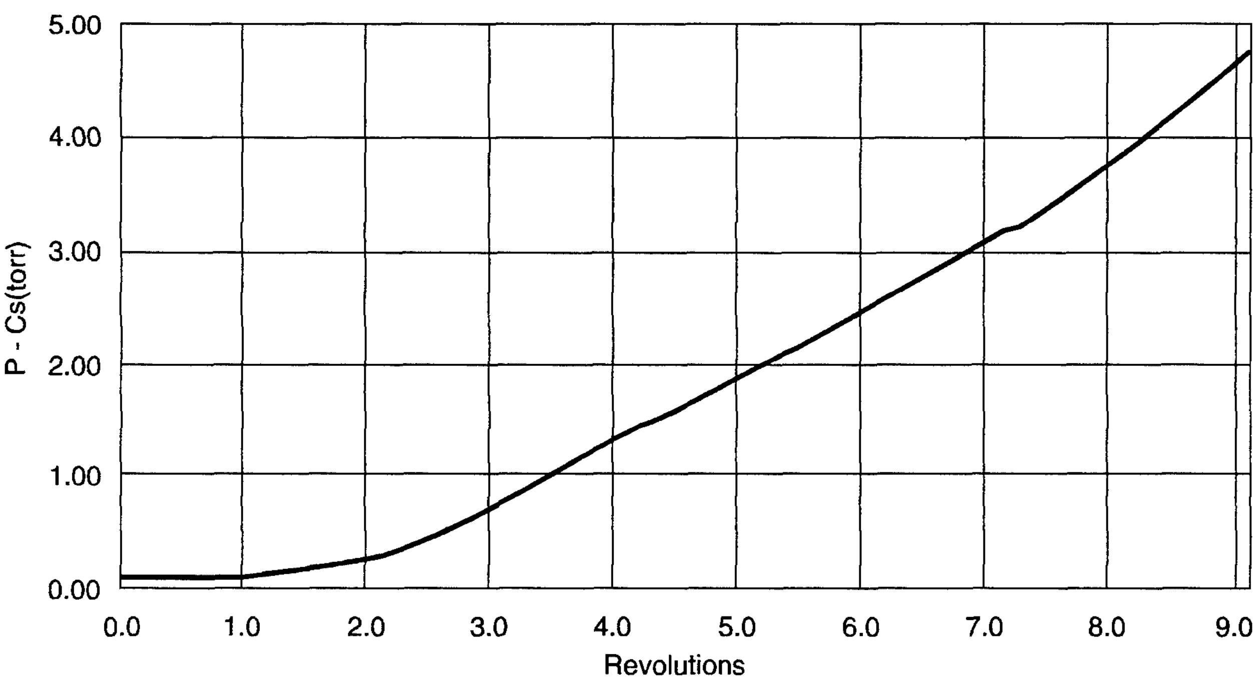


Figure 15. Cesium throttle valve calibration curve.

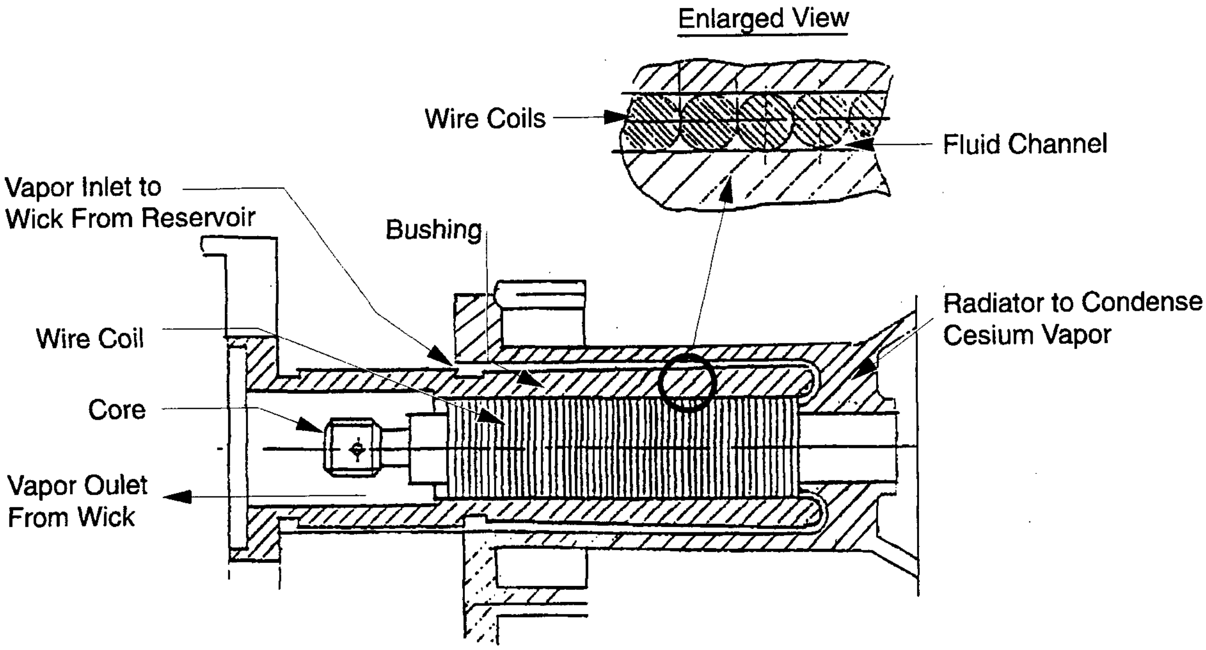


Figure 16. Cesium source wick

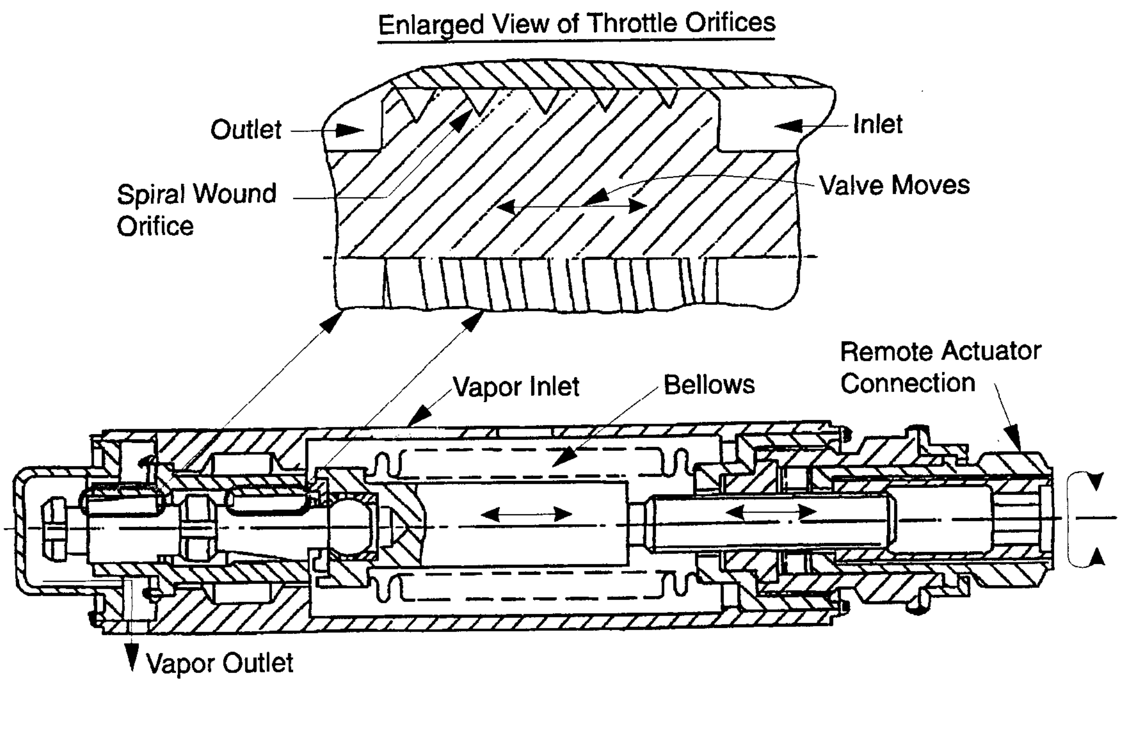


Figure 17. Cesium source throttle valve.

1.6.5 Gas Supply Systems

Two gas supply systems, helium and a gas mixture of helium and carbon dioxide, were incorporated in the design of the TOPAZ-II space power system, as illustrated by the schematic in Figure 3. Each system was connected to a separate 40-liter stainless steel bottle, illustrated by Figure 18, that was located with the radiator cone and attached to the structure. The helium system supplied inert gas to the plenum containing the TFE electrical connections to cool and prevent arcing within the plenum and to the space separating the TFE collectors from the NaK coolant channels to increase heat transfer and to control temperatures. The other system, which supplied a gas mixture of carbon dioxide and helium, was connected to the space surrounding the zirconium hydride moderator within the reactor vessel and was used to reduced hydrogen leakage through potential cracks in the diffusion barrier.

The volume accumulator, designed to accommodate expansion of the NaK coolant from ambient temperature to operating system temperatures, was pressurized with argon and hermetically sealed.

The radiation shield was pressurized with helium and hermetically sealed to increase thermal heat transfer from the lithium hydride to the stainless steel container.

1.6.6 Startup Unit and Battery

The startup unit and battery subsystem, illustrated by the electrical diagram in Figure 19, was designed to supply intermittent electrical power to the EM pump to prevent freezing of the NaK coolant in the radiator during the period from lift-off until power was provided by the EM pump section TFEs. The battery power was switched on when the lower radiator manifold temperature dropped below 5°C (278 K) and remained on for approximately 90 s.

During reactor startup in orbit, the startup unit and battery subsystem was designed to provide a continuous supply of electrical current to the EM pump. Electromagnetic switches, remotely controlled from the spacecraft, connected the startup unit to the EM pump. After completion of reactor startup, the EM pump would be disconnected and the startup battery electrolyte vented through two orifices to space.

The reactor startup unit and battery were separate components that were designed to be removed during thermal vacuum performance testing and installed during pre-launch operations.

1.6.7 Structures

The three main structural members of the TOPAZ-II system were the frame, shield, and reactor vessel. The tripod frame, illustrated by Figure 20, was located within the conical radiator and provided the mechanical interface with the spacecraft. The frame supported the radiation shield, radiator, a volume accumulator, two gas bottles, coolant piping, and electrical cables. The upper end of the frame was attached to the bottom of the radiation shield which provided structural support for the reactor assembly, EM pump, coolant piping, and automatic control drive motor.

The radiation shield had attachments at the upper end for lifting and transportation of the system within the test facility. Six legs attached to the top of the radiation shield were connected to and supported the reactor assembly, as indicated by Figure 21.

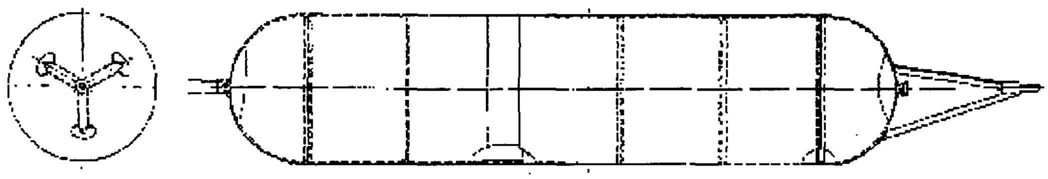


Figure 18. TOPAZ-II gas bottle.

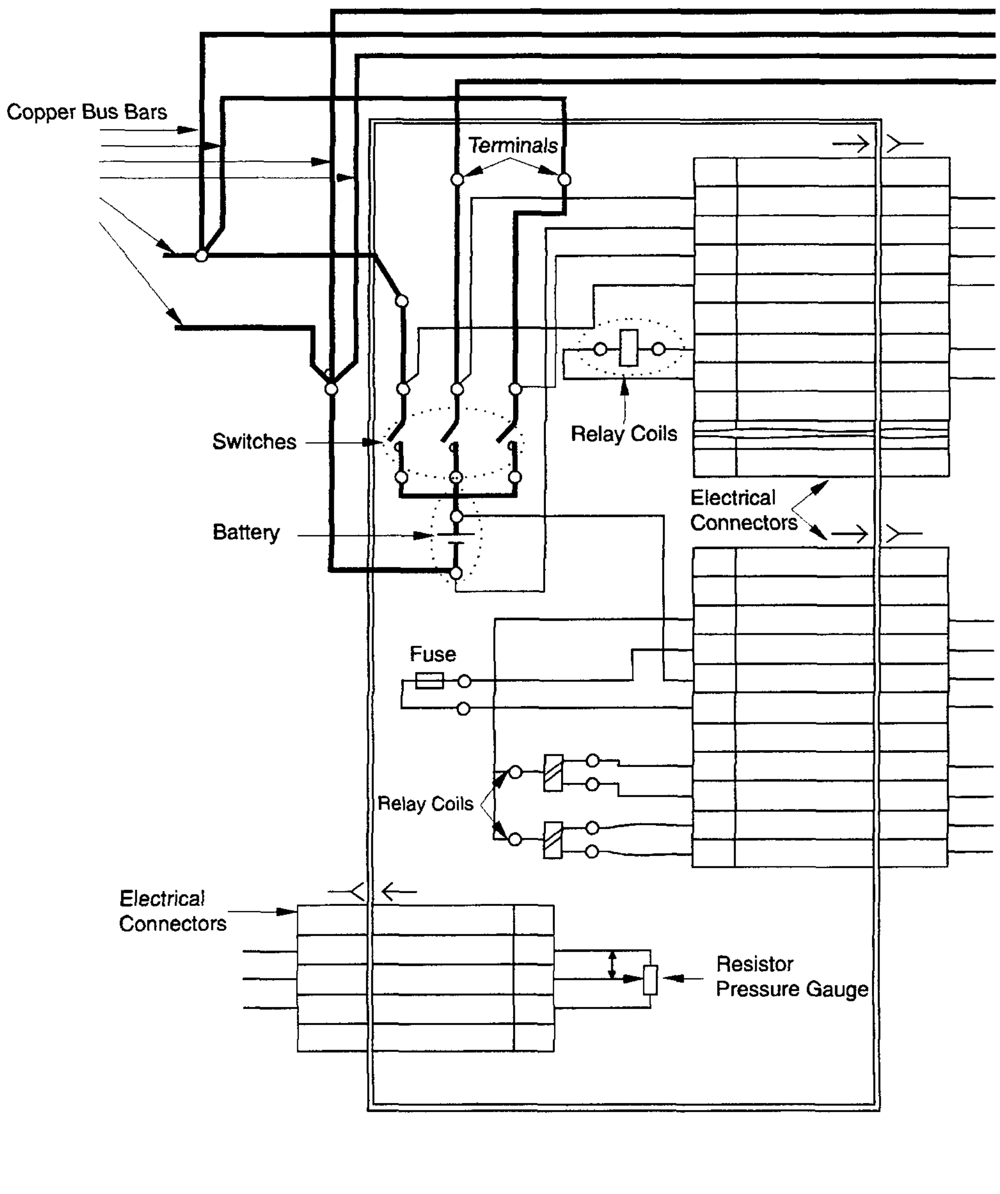


Figure 19. TOPAZ-II startup unit and battery schematic.

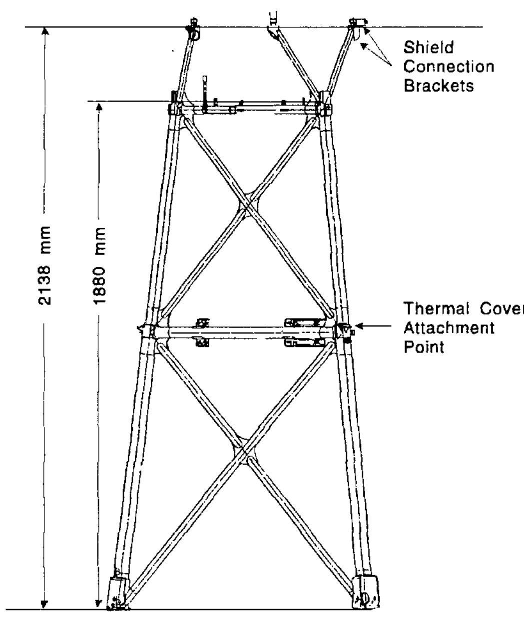


Figure 20. TOPAZ-II main support frame.

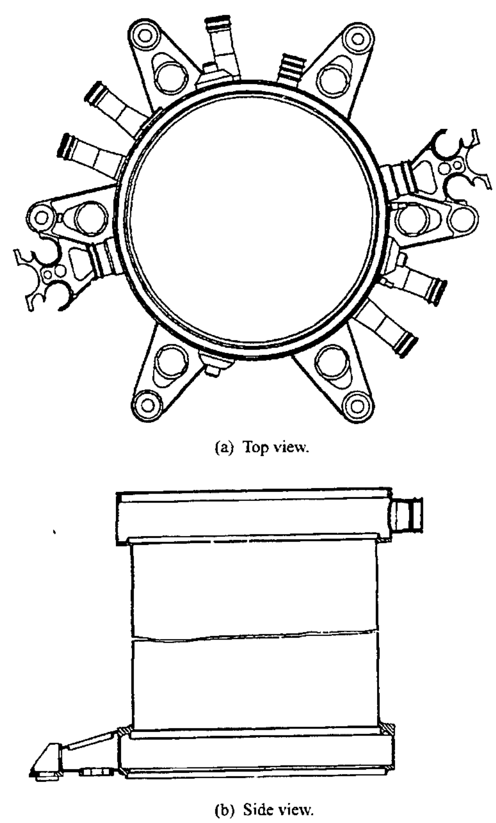


Figure 21. TOPAZ-II reactor assembly support structure.

1.6.8 Thermal Cover

The conical-shaped thermal cover, illustrated by Figure 22, was designed for launching of the TOPAZ-II system with the reactor above the radiator. The thermal cover was comprised of three conical segments that covered the TOPAZ-II system. The thermal cover was placed around the system to limit heat losses prior to and after launch and was used to keep the NaK coolant from freezing during orbital injection and reactor startup. When the temperature in the lower collector of the radiator reached 100°C (373 K), an automatic signal would be sent to power the explosive squibs at a central lock, which would then release cables that held the thermal cover in place before it was ejected. When the thermal cover was ejected, six mechanical relay switches were closed and electrical signals were sent to the spacecraft to verify release of the thermal cover segments.

1.6.9 Electrical System

The TOPAZ-II required conditioned electrical power to operate the automatic control system (ACS) that contained the reactor control and monitoring system. The ACS maintained the preset mode of operation of the reactor system. The interconnections between the ACS and TOPAZ-II system are illustrated by Figure 23.

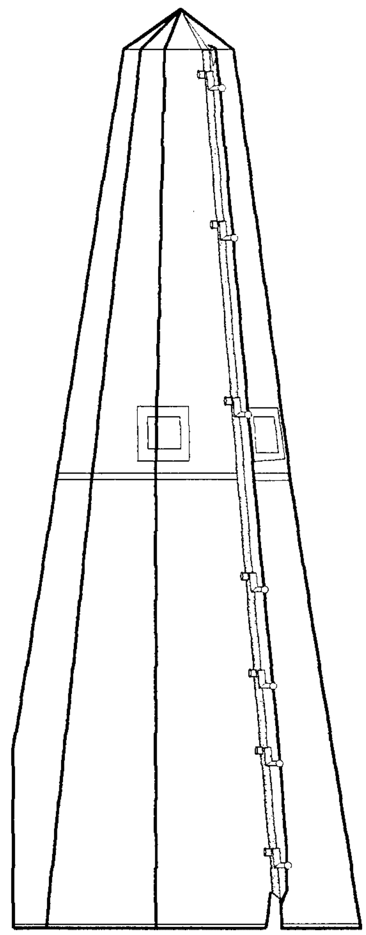
1.6.10 Automatic Control System

The ACS performed the following functions:

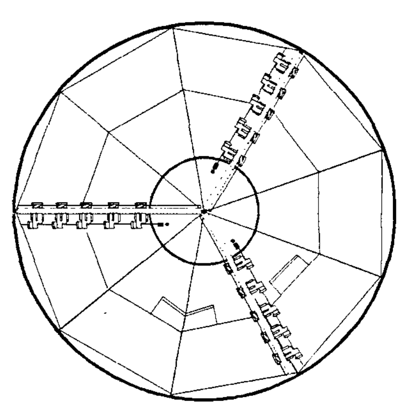
- Conducted startup and stabilization of the reactor system at rated power;
- Maintained the system at rated power;
- Maintained the output voltage of the system;
- Connected the storage battery to the system before launch;
- Monitored charging, discharging, and recharging of the storage battery when the system was operating;
- Provided telemetric control of the system parameters during pre-launch, launch, orbit injection, and during operation in orbit; and
- Performed reactor shutdown when telecommunication between ground control centers and orbiting TOPAZ-II system was lost for a preset, extended period.

The ACS consisted of the following functional components: command and telemetry system, automatic regulator system, and power supply system.
The command and telemetry system:

- Received, analyzed and multiplied the ground control commands;
- Converted sensor signals received from the TOPAZ-II system, the automatic regulator system or reactor control unit, and the power supply system to standard telemetric information; and
- Ensured execution of the automatic regulator system commands to maintain the required reactor power level, to shutdown the reactor, and to eject the reflector controls for emergency shutdown.



(a) Side view.



(b) Top view.

Figure 22. TOPAZ-II thermal cover.

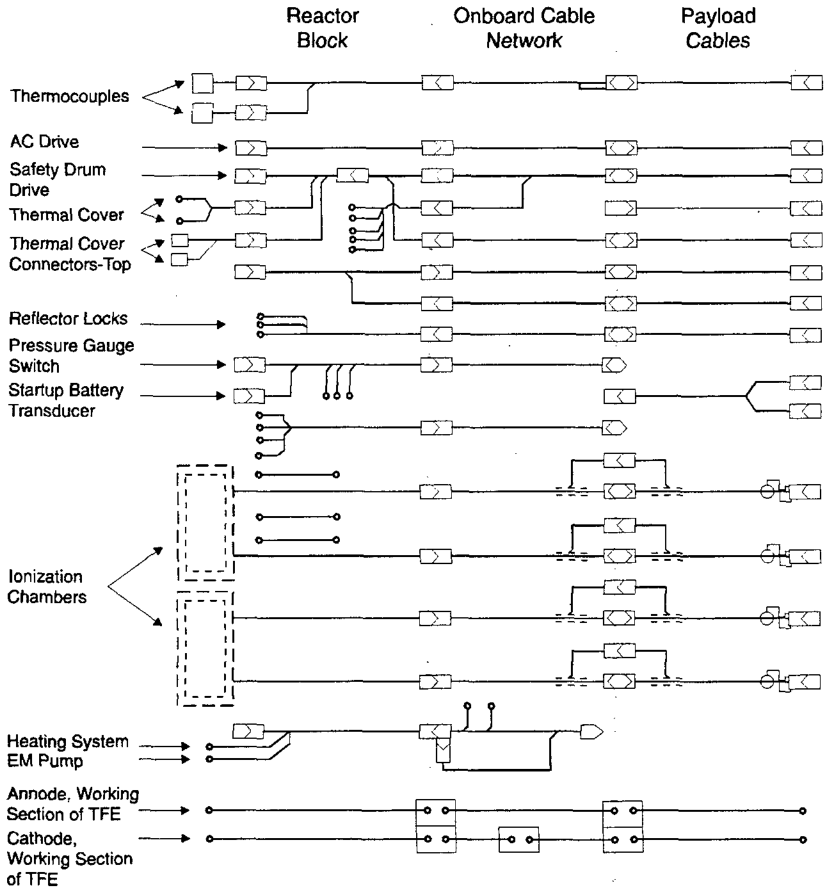


Figure 23. TOPAZ-II electrical system block diagram.

The automatic regulator system:

- Received and processed signals from the TOPAZ-II system sensors, automatic control current sensors, and ground control center;
- Controlled the reactor during startup in orbit, at rated power levels and working conditions, and during shutdown using preset logic; and
- Enabled control of the reactor from the ground control center by using the automatic control drive.

The power supply system:

- Maintained the preset electrical load during the reactor startup period and during any changes in the mission/application load demand;
- Stabilized the voltage output at the TOPAZ-II system interface during rated system operation;
- Maintained power supply voltage of the automatic regulator system and the command and telemetry system; and
- Maintained the storage battery functions according to preset logic.

During non-nuclear ground testing, the functions of TOPAZ-II power system and ACS were checked by using a test simulator provided by the Russians.

1.6.11 Instrumentation Sensors

A variety of sensors, listed in Table 6, were strategically located on the TOPAZ-II system and permitted monitoring of system parameters during pre-launch preparations, evaluation of system condition prior to and during orbital startup, and assessment of performance and control during steady-state operation.

Two pairs of thermocouples monitored the reactor coolant outlet temperature; 14 resistance temperature detectors (RTDs) monitored the reactor inlet, radiator inlet, radiator collector, radiator outlet, and the automatic control drive. Five membrane-potentiometer pressure transducers monitored pressures of the helium in the reactor plenum, helium and carbon dioxide gas in the moderator, helium in the radiation shield, argon in the NaK volume compensator, and the electrolyte in the startup battery.

Position sensors indicated positions of safety drums, control drum drive assemblies, cesium supply valve, and ejection of the thermal cover. Two ionization chambers, each containing ~1.4 g of U_{235}, provided information on the neutron level of the reactor. Performances of the work section and pump section TFEs were provided by voltage and current taps located on the TOPAZ-II system power bus.

1.7 TOPAZ-II SYSTEM TESTABILITY

The TOPAZ-II system design had three significant features that enhanced testability, transportation, storage, safety, and security of enriched nuclear fuels: (1) the design of the single cell TFEs permitted the reactor fuel to be installed and removed easily during sub-critical and zero power nuclear testing and transportation between facilities; (2) the TFE design permitted electric heaters to be inserted in place of the nuclear fuel and enabled system testing at operating temperatures and power levels in a non-nuclear test facility; and (3) the cesium system design permitted optimization of the cesium pressure during acceptance testing for each TOPAZ-II system (Schmidt #13).

1.8 TRANSFER OF SPACE POWER SYSTEM TECHNOLOGY

Opportunities for transfer of new information and technology to U.S. personnel were provided as each phase of the TOPAZ-II system test program was implemented and completed. The transfer of significant information and technology occurred as Russian and U.S. specialists worked side-by-side on tasks directly related to the Ya-21U tests.

Table 6. List of TOPAZ-II Ya-21U system sensors.

Sensor	Parameter Measured	Range	Output Signal
07.01	Pressure of helium in reactor plenum (mm Hg)	0 - 306	0 - 6 V
08.01	Pressure of helium in radiation shield (kg/cm^2)	0 - 1.6	0 - 6 V
26.01	Pressure of oxidizer in moderator (kg/cm^2)	0 - 3.5	0 - 6 V
30.01	Pressure of argon on volume compensator (kg/cm^2)	0 - 2.5	0 - 6 V
21.07	Temperature - reactor outlet coolant - z (°C)	0 - 650	Thermocouple
21.08	Temperature - reactor outlet coolant +z (°C)	0 - 650	Thermocouple
21.10	Temperature - inlet radiator collector +y (°C)	0 - 650	17 - 57 ohm
21.13	Temperature - outlet radiator collector -z -y (°C)	0 - 650	17 - 57 ohm
21.14	Temperature - outlet radiator collector +y +z (°C)	0 - 650	17 - 57 ohm
21.15	Temperature - outlet radiator collector +z -y (°C)	0 - 650	17 - 57 ohm
21.16	Temperature - outlet radiator collector -y -z (°C)	0 - 650	17 - 57 ohm
21.17	Temperature - outlet radiator collector -z (°C)	0 - 650	17 - 57 ohm
21.18	Temperature - radiator return pipe -z (°C)	0 - 650	17 - 57 ohm
21.19	Temperature - radiator return pipe +z (°C)	0 - 650	17 - 57 ohm
21.20	Temperature - pre-heater outlet pipe +z (°C)	0 - 650	17 - 57 ohm
21.21	Temperature - pre-heater outlet pipe +z (°C)	0 - 650	17 - 57 ohm
21.22	Temperature - radiator return pipe +z (°C)	0 - 650	17 - 57 ohm
21.23	Temperature - radiator return pipe +z (°C)	0 - 650	17 - 57 ohm
21.24	Temperature - radiator return pipe -z (°C)	0 - 650	17 - 57 ohm
46.01	Position - AC drive output shaft (degree)	0 - 190	
46.02	Temperature - AC drive unit (°C)	0 - 150	33 - 49 ohm
46.03	Pressure - argon in AC drive unit (kg/cm^2)	0 - 2.5	0 - 6 V
46.04	Temperature - control drive unit connector (°C)	0 - 250	Thermocouple
69.01	Temperature - pressure gage unit (°C)	0 - 200	Thermocouple
69.02	Temperature - pressure gage unit (°C)	0 - 200	Thermocouple
52.01	Current - ionization chamber - #1 (A)	10^{-9} - 10^{-6}	10^{-9} - 10^{-6} A
52.02	Current - ionization chamber - #2) (A)	10^{-9} - 10^{-6}	10^{-9} - 10^{-6} A
52.03	Resistance - ion chamber insulation-#1 (ohm)	10^{6} - 10^{9}	10^{6} - 10^{9} ohm
52.04	Resistance - ion chamber insulation-#2 (ohm)	10^{6} - 10^{9}	10^{6} - 10^{9} ohm
67.01	Voltage - EM pump (VDC)	0 - 1	0 - 1 VDC
67.02	Voltage - reactor work section terminals (VDC)	0 - 35	0 - 35 VDC
67.03	Voltage - work section/spacecraft connects (VDC)	0 - 35	0 - 35 VDC
67.05	Voltage - EM pump section (VDC)	0 - 1	0 - 1 VDC
67.41	Voltage - TFE #28 anode (VDC)	0 - 2	0 - 2 VDC

1.8.1 Opportunities for Technology Transfer

Transfer of space power system technology occurred during the following activities:

- Planning, assessment, and negotiation with Russians to obtain the following:
  - TOPAZ-II systems and components;
  - System test equipment, fixtures, and test instruments;
  - Key procedures and materials information on TOPAZ-II systems; and
  - Technical and specialist support services.

- Reviews and assimilation of information from delivered Russian TOPAZ-II documents, for example:
  - Drawings and descriptions of the system, components, and subsystems;
  - Operation and calibration procedures of test equipment and test data; and
  - System performance histograms, data, and correlations.

- Working together on assigned tasks, for example:
  - Sharing of personal techniques, skills, and experience gained from previous technical assignments and TOPAZ-II test operations;
  - Joint efforts to identify and fulfill TOPAZ-II training requirements;
  - Joint efforts to identify Ya-21U testing problems or corrective actions; and
  - Joint efforts to summarize and report results of completed Ya-21U tests.

- Installation, calibration, and operation of the Baikal test stand including:
  - Checkout of the Baikal test stand vacuum systems and vacuum chamber;
  - Connection of the cesium evacuation system to Ya-21U;
  - Installation of the TISA heaters for thermal vacuum system testing; and
  - Checkout of the NaK leak detection devices.

- Thermal vacuum testing of Ya-21U including:
  - TFE ignition and voltage profiles;
  - EM pump and pump section performance assessments;
  - NaK system and radiator performance;
  - TISA heater and Ya-21U system outgassing;
  - Experimental testing and assessment of results;
  - Thermionic converter performance with and without a thermal shield;
  - System shutdown and functional testing;
  - Slow and fast orbital startup simulations;
  - Emergency shutdowns of electric power supply system;
  - Cesium system leak detection and assessments; and
  - Oxide contamination and effects on TFEs and cesium supply system.

- Mechanical modal, vibration and shock testing of the Ya-21U system including:
  - Test fixture design and test system support structure;
  - Accelerometer location, calibration, and pre-test checkout;
  - Sinusoidal and random vibration sweeps from 5 to 200 Hz;
  - Assessment of structural response to excessive vibration forces; and
  - Leak detection of TFEs and repair of the cesium system vapor vent line.

- Ground support equipment use, for example:
  - Shipping and storage container;
  - Lifting and rotation fixtures; and
  - System functional checkout consoles.

1.8.2 Nuclear Reactor Assembly

Information was obtained frequently during unplanned discussions of manufacturing steps, materials, quality control procedures, functional and structural design of components, performance assessment techniques, and thermal and structural stress limitations. The following are examples of this information:

(1) The composition and function of the mixed helium and carbon-dioxide gases supplied to the encapsulated moderator blocks in the reactor core;

(2) The temperature limitations of the zirconium-hydride moderator material that must not be exceeded during non-nuclear testing and the hydrogen diffusion that occurs during operation at high power levels for extended periods of time; and

(3) The potential for hydrogen diffusion into the liquid metal coolant, helium gas plenum, and inter-electrode spaces between the TFE emitters and collectors.

A more detailed description and understanding of the reactor control drive mechanism, which was actuated by a single drive stepper motor, was obtained during the functional performance and calibration checks prior to thermal vacuum system testing. A significant feature of this mechanical design was the amount of backlash provided in each of the control drums to accommodate the neutronic coarse and fine control required during system startup and steady-state operation of the reactor system.

Other examples of frequent, unplanned discussions which enhanced technology transfer related to safety features of the reactor assembly design; reactor fuel, fuel loading procedures, and gas venting during extended operation at design power levels; and design of the structural members above the radiation shield that support the reactor assembly.

1.8.3 TFE Work Section

Information was obtained on the TFE manufacturing steps, materials, quality control procedures, functional and structural design, components, performance assessment techniques, and thermal, electrical, and structural stress limitations; for example:

(1) Detailed descriptions of the TFEs installed in Ya-21U;
(2) Changes in the fabrication process, and the performance checks made before assembly of the work section; and
(3) Checks and visual inspections of each TFE prior to and after thermal vacuum system testing and the interpretation of variances of data obtained during the checks and visual inspections.

Other examples of technology transfer during the Ya-21U test program included:

(1) Careful installation of the voltage taps to the TFEs to prevent electrical shorting;
(2) Installation of the fragile TISA heaters and attachment of power cables;
(3) Slow initial heat-up of the reactor and work section to ensure sufficient outgassing of the TISA heaters and TFE emitters;
(4) Careful balancing and leveling of power to the TISA heaters required during startup, steady-state, and shutdown of the system; and
(5) Potential for severe thermal stressing of both TFEs and the work section during Baikal test stand/facility power interruptions of more than 2 s duration.

The description and explanation of TFE ignition, potential for electrical arcing within the TFEs, and work section instability during the heat-up to system operating temperatures were provided during Ya-21U testing. The information and explanation permitted an in-depth understanding of TFE design features and the inter-relationship between emitter and collector temperatures, interelectrode gap pressure, cesium vapor pressure, electrical load resistance and current, and the need for control of these parameters during system startup in space.

The discovery of very small cesium leaks in the upper hermetic seals of two TFEs after completion of more than 3,500 hr of system operation provided an opportunity to observe the effects on system performance of similar leaks that might occur during operation in space. Although the effect on performance was undetectable at first, additional information on the performance of the thermionic converter work section and cesium system was gained during the investigation and evaluation efforts. When the cesium system leak rate increased significantly following unplanned emergency system shutdowns and after completion of the mechanical vibration and shock tests, a more complete understanding of the integrated thermionic work section and cesium system resulted.

As a consequence of the increased cesium system leak rate and inadvertent entrance of air into the cesium system, additional information was gained on the effects of oxygen contamination of the converter work section and specifically the interelectrode gaps of the TFEs.

The observation that the thermionic converter continued to produce approximately 50% of the design power after being severely overstressed by the unplanned emergency shutdowns and more than 30 min of vibration in excess of 4 g during the mechanical tests was an impressive demonstration of the technology and durability of the Ya-21U space power system.

1.8.4 Pump Section

Although the three parallel connected TFEs of the pump section were the same as those in the work section and were operated in the same thermal-cesium environment, all other parameters were different. Accordingly, optimum conditions for maximum power and efficiency of the work section did not provide optimum conditions for EM pump TFEs; for example, current provided to the EM pump was most important. The Russian choice of three TFEs instead of two, four, or more to drive the EM pump enabled the power system to be operated with ~20% decrease in the NaK flow if one TFE in the pump section should fail. The result would increase the reactor NaK outlet temperature and decrease the reactor NaK inlet with only a slight change in the average core temperature. The reduction in the reactor NaK inlet temperature will affect operation of the cesium source and supply system and would require additional evaluation of long term performance.

1.8.5 Cesium System

The design of the autonomous cesium reservoir and pressure regulation system for thermionic power conversion systems represented high technology not yet demonstrated by U.S. system designs. Also, less was known about the Russian single source cesium supply system even though it was described and discussed in detail by Russian specialists during testing of the V-71 and Ya-21U systems.

The lack of an in-depth knowledge of the characteristics and performance of the cesium system was the result of several factors. First, there were no pressure sensors on the TOPAZ-II systems between the cesium pressure regulation throttle valve and the reactor cesium plenum to indicate the response and variation in cesium pressure due to TISA heater power changes, temperature changes of the reactor system and cesium source, and NaK flow variations during system startup.

Second, Ya-21U system cesium vapor pressures were based on static calibrations performed on the cesium source and regulator when it was installed on the cesium test rig during component testing. Estimated and recorded cesium pressures were based on the position (number of turns) of the throttle valve operator that penetrated the Baikal test stand vacuum chamber wall.

Thus, a variance in performance of the Ya-21U work section between Russian and U.S. test results could be related to an actual change in total pressure within the cesium system which may not be related to the calibration pressures indicated by the throttle valve position. For example, slight oxygen contamination of the cesium system would cause variations in the performance of each TFE for a particular setting of the cesium throttle valve; and, the optimum cesium pressure, according to the throttle valve calibration, would shift accordingly.

The extent and effect of the oxygen contamination was thought to be related to a known leak rate and duration of the leak(s). Additional testing of the Ya-21U work section and cesium reservoir and pressure regulator will be required to understand the sensitivity, subtle characteristics, and unique design features of the cesium system and the effect of oxides on cesium system pressure versus throttle valve positions.

1.8.6 NaK Coolant System

Russian NaK system technology was found to be similar to that developed by the U.S. Systems for Nuclear Auxiliary Power (SNAP) Program during the period from 1959 to 1973 (Schmidt #16). The differences between NaK system technologies and system designs were based on the following:

- Russian materials and processes, used to fabricate the radiator headers and tubes, contained inclusions (slag) that caused NaK leaks when the radiators were operated at design temperatures. Extensive radiography was required to sort out the flawed materials and parts. NOTE: At the beginning, the U.S. had a similar problem with machined parts, which was solved by requiring fabrication materials to be triple-vacuum, arc-melted, and that all metal forming equipment be super clean.

- The purity of NaK coolant in TOPAZ-II systems was of great concern to Russian specialists. The Russian process for charging TOPAZ-II coolant systems with NaK required considerable preparation before NaK loading, a long period for NaK circulation, and many samples to determine the final impurity levels before system sealing and separation. This concern for purity could have been related to the original purity of the NaK furnished by Russian suppliers and the capability of the charging system to remove the impurities.

- Most, if not all, welding done on the Russian NaK coolant system was done using hand-held welding equipment. Welding of thin-walled tubing and shaped header sections required the combination of considerable skill and uniform high quality materials to assure failure-free NaK systems.

- The integrity of the TOPAZ-II NaK systems after initial charging required operation of the NaK systems at design temperatures for more than 1,000 hr to identify the infantile failures and demonstrate successful repairs.

For the above reasons, extended operation at design temperatures before and after mechanical tests was included in the original Ya-21U test plan to demonstrate the integrity and durability of the NaK system (Schmidt #6).

2.0 RUSSIAN PROGRAM

2.1 INTRODUCTION

Ya-21U represented 20 years of Russian space nuclear thermionic power system technology development from 1969 to 1989. The status of this technology was demonstrated by the results of Russian inspections, system tests, modifications, repairs, and performance evaluations of Ya-21U prior to its shipment to the U.S. The TOPAZ-II and Ya-21U system information provided by Russian documents, when combined with that obtained from Russian specialists, established the technology baseline upon which U.S. specialists began their evaluations and assessments. Variances between Russian and U.S. Ya-21U test results, evaluations, and assessments were acknowledged and thoroughly explained to determine the source or cause of the variances and their impact on the perceived status of the Russian technology. In a very short period of time before the Ya-21U system test program began, U.S. specialists were required to understand Russian technology and what was represented by the delivered TOPAZ-II systems. A few of the significant technology issues are provided in this Section of the report.

Overall, the TOPAZ-II Ya-21U system design was sophisticated, very robust, and durable. The system's performance was predictable, stable, and repeatable within the system design operating range and conditions. These characteristics of the TOPAZ-II design were demonstrated previously by 19 Russian system tests performed between 1970 and 1989.

Ya-21U was subjected to many thermal cycles during Russian manufacturing, acceptance, and the additional testing sequence. Some thermal cycles were directly related to the NaK coolant system leaks that had previously plagued development of TOPAZ-II space nuclear power systems. The previous coolant system leaks occurred mostly in the radiator collectors and tubes and one leak also occurred in a coolant channel of an EM pump.

The cause of the leaks was attributed to the use of low quality stainless steel materials during fabrication of NaK system parts and lack of timely radiographic inspections to detect the flawed materials. Ya-21U NaK leaks were repaired and the system tested extensively at high temperatures after the last detected leak.

NOTE: The potential for future NaK leaks in Ya-21U was uncertain prior to the start of thermal vacuum system evaluation tests in the U.S. The perceived impact of NaK system leaks on future tests and use of TOPAZ-II systems was significant.

The last non-nuclear, thermal-vacuum, high-power test performed on Ya-21U by Russian specialists demonstrated the capability of the TOPAZ-II design to produce 5 kW of power at 28 - 30 V. However, the top section of the reactor was overheated by the TISA heaters during this high-power test and may have damaged the upper parts of the thermionic fuel elements.

NOTE: Subsequent thermal vacuum and mechanical system tests performed by TSET on Ya-21U explored the effects of overheating the TFEs. The results obtained by TSET are provided in Sections 3 and 4 of this report.

2.2 THE HERITAGE OF YA-21U

The Russian TOPAZ-II space reactor development program began in 1969. Twenty-six (26) systems were manufactured, and 19 systems were tested during the period from 1970 to 1989 to assure that flight systems would provide 5 to 6 kW of electrical power for space missions lasting 1-3 years. The basic design remained the same, although a number of design changes were made during the development period (Ogloblin, #17).

The Russian test program, which ended in 1989 due to serious economic problems, included 13 non-nuclear and 6 ground nuclear TOPAZ II system tests. The Russians performed four types of system tests: thermal management, mechanical, electrically heated thermal-vacuum, and ground nuclear.

Ya-21U was the first TOPAZ-II system designed and modified for an operating life of more than 3 years. This lifetime was achieved by use of a modified reactor, improved TFEs, and a cesium reservoir and regulator that contained a larger supply of cesium (Ogloblin #17).

The manufacture of Ya-21U began in 1982 and was completed in 1989. Final assembly of the system was completed in December 1987. Ya-21U was then transported to the Baikal test stand #3 for control and acceptance tests. Incoming inspections were performed and installation in the vacuum chamber and checkout of the system were completed before control tests were started in August 1988.

In September 1988, control tests were terminated by an emergency cool-down of the system, which was caused by a Baikal test stand heater failure that had resulted from a NaK leak of the heat rejection system. From October through December 1988, efforts were made to find the NaK leak, which was determined to be in the lower section of the lower radiator manifold between a radiator support bracket and the NaK system drain pipe. The NaK leak was repaired during the period from January through March 1989. Control tests of Ya-21U were restarted in March 1989 and completed in August 1989.

Acceptance tests of Ya-21U began following completion of the control tests. The acceptance tests were performed at a constant thermal power level of 85 kW, using electric TISA heaters. The acceptance tests were performed to demonstrate performance and reliability of the NaK system prior to the nuclear and flight tests of subsequent prototype systems. The planned 500 to 1,000-hr acceptance tests included optimization of the cesium vapor pressure and determination of the system work section current-voltage characteristics. Initially, specific tests were planned to take between 2,000 and 3,000 hr; however, they were first interrupted and then terminated due to the loss of funding. Ya-21U was then isolated and secured.

In January 1990, a decision was made to conduct thermal vacuum tests at a thermal power level of 123 kW using TISA heaters to demonstrate that the system work section could produce more than 5 kWe. These tests were performed successfully during the period from February through April 1990 and were followed by system shutdown and isolation from the Baikal test stand.

During the 4.5-yr period following assembly, Ya-21U was operated at temperatures above 100°C (372 K) for ~5,900 hr. This period included operation at temperatures above 350°C (623 K) for ~4550 hr and operation at temperatures above 450°C (723 K) for ~3,700 hr. The Ya-21U work section produced power in excess of 2 kWe for ~2,500 hr and produced 5 kWe for a period of 45 hr during this period. Ya-21U was removed from the Baikal test stand in July 1990 and stored under a protective cover until April 1992.

During April 1992, Ya-21U was placed in a container and preparations made for shipment to the U.S. In May 1992, Ya-21U was delivered (along with the V-71 system) to Albuquerque, NM, by a U.S. Air Force C-5A cargo plane.

2.3 YA-21U SYSTEM MANUFACTURING

The manufacture of Ya-21U was performed according to the technical documents and processes developed during previous TOPAZ-II manufacturing efforts. The TOPAZ-II manufacturing process consisted of two major stages. The first stage followed the manufacture and assembly of the parts, components, and subassemblies. The second stage included the control and acceptance tests performed between 1988 and 1989 (Ogloblin, #17).

2.3.1 First Stage of Manufacturing Process

The first stage included assembly of the reactor unit, leak checking of the TFE cavities, physical measurements of geometry, electrical circuits, mass, and other characteristics. This stage was completed before the beginning of control and acceptance tests.

During the first stage, the quality of Ya-21U documents and processes were evaluated based on the number of deviations from the following design documents and flaw reports:

- *Analysis of Deviations from Design Documentation Allowed During Ya-21U Manufacture: 182-01-0021TU1, #1102-03/29, from 06-14-89*
- *Report on Quality of Ya-21U Manufacture: 182-01-0021TU1, #102-03/29 from 06-28-89*
- *Technical Conditions on Reactor Unit: 182-01-0021TU1 and 182-01-0021TU2*
- *Technical Decisions on Additional Tests of Ya-21: #13-101/16-89 from 03-10-89.*

The total number of change notices in the reactor unit design documentation was 3,037. Of these, 15% required Ya-21U modifications. The change notices were due to design and manufacturing improvements, design changes related to test results, and errors in design documents. The number of errors in design documents did not exceed 1%.

During Ya-21U manufacture, 86 approval cards were issued, which was half the average number issued on each of the previous 12 reactor units. Most of the deficiencies were due to the following:

Technical preparation	21.6%
Technical documentation	19.9%
Reactor unit design documentation	16.9%

Most deviations were caused by the following:

Discrepancies in geometric specifications in Ya-21U design documents	39.5%
Material and component replacement	15.1%
Exceeding useful life	10.5%

Most flaws were due to the following:

Violations of surface and coating specifications	24%
Violations of geometric specifications	23%
Non-hermetically welded joints	9%

Most flawed parts were removed from the manufacturing process, while others were repaired. Examples of the latter were a pipeline, a lower manifold section, two pipes on the radiator , and the automatic control drive parts.

The pipeline repair was required because of a hole under a cover plate that had been welded onto the pipeline. The damaged section of the pipe was removed and replaced, the cause of the defect studied, and leak checks were performed to demonstrate that the leak had been eliminated.

During radiator manufacture and after copper cover plates (fins) were welded, four burns and a 0.5-mm dent occurred on the lower section of the manifold. Burns were also found on two other pipes of the radiator. The defects were eliminated and checked by testing.

Leak tests of an automatic control drive part revealed a leak. The leak was eliminated by welding two half rings on the part that covered the leaking area.

Analysis of deviations from design documentation indicated that the deviations would not affect the performance and reliability of Ya-21U during proposed system tests with electric heating.

2.3.2 Second Stage of Manufacturing Process

The second stage of manufacturing included the control and acceptance tests performed during a 1.5-yr period that started in 1988 and was completed in 1989. The control tests included preparation of the cavities to be filled with gas, gas supply to the cavities, cesium pressure adjustment, system characteristics analysis, and comparison with the technical specifications.

Control testing was terminated after 1.5 months of operation due to a NaK leak that caused failure of the electric heaters used to heat the Ya-21U radiator. During the period from October 1988 to January 1989, the leak was located, analyzed, repaired, checked, and eliminated. The

leak occurred in the lower manifold in the area near the drain line. The Baikal test stand parts and Ya-21U were cleaned, damaged Baikal test stand equipment was replaced, and the vacuum chamber suspension was replaced with a similar unit. The damaged area of the lower manifold was removed and inspected to determine the cause for failure. The inspection revealed a transverse crack (3 mm in length) in the damaged area. It was postulated that the crack was caused by impurities in the lower manifold wall. The crack probably developed from conglomerate materials in the damaged area that was located near the internal surface of the lower manifold.

NOTE: The Prometheus Metallurgical Laboratory said the crack was not related to the hidden impurities in the lower manifold materials and Russian specialists stressed that the leak was caused by the large number of thermal cycles.

After completion of the control tests, acceptance tests of Ya-21U were performed. The acceptance tests included rapid startup and operation of the system at TISA heater power levels of approximately 85 kW and work section power levels above 2 kWe. The characteristics of Ya-21U were determined and registered in the service log of the system.

Following completion of the control and acceptance tests, the evacuation system was disconnected in accordance with the technical decision on additional tests of Ya-21U. The remainder of Baikal test stand systems were disconnected from Ya-21U in July 1990.

Thirty-six design solutions were issued during the control and acceptance testing (24 were issued during 1987 and 1988 and 12 were issued during 1989). These solutions were not analyzed to determine the impact of the deviations. However, the electric power tests of Ya-21U confirmed the system's performance. Russian specialists recommended analysis of some of the deviations and design solutions (listed below) to determine Ya-21U's applicability for other mechanical and nuclear tests which had been proposed during future TOPAZ-II demonstration tests.

1. DS #526-0348-88: Absence of R_{gen} circuits on DO and DAKO sensors.
2. DS #526-0002-89: Decreased insulation resistance of some circuits due to NaK leaks was recorded, which resulted in temperature differences on resistance sensors measuring the same temperatures.
3. DS #526-0195-89: Decreased insulation resistance on TFE gap #7 was recorded as 8 instead of 15 ohms.

2.4 BAIKAL TEST STAND THERMAL VACUUM TESTS

The Baikal test stand thermal vacuum tests included the following (Ogloblin, #17):

1. Incoming inspection of Ya-21U;
2. Preparations for control testing, which included checks, evacuation, and leak testing of Ya-21U system cavities before heating;
3. Control testing, which included Ya-21U thermal vacuum processing at 100 to 600°C (373 to 873 K), and charging of the gas cavities, followed by sealing and inspection;

4. Acceptance testing, which included Ya-21U heating at specified heating rates and operation at specified parameters, power levels, and temperatures.

2.4.1 Thermal Vacuum Control Tests

After installation on the Baikal test stand, inspections of Ya-21U were completed and reported *(Protocol of Consideration of "Report on Ya-21U Incoming Inspection," 3107-07/111 from 05-27-88; and Report of Ya-21U incoming Inspection, #505-05-1/82 from 03-29-88).*

After leak testing of the system cavities, they were filled and the system heated to a temperature of 550°C (823 K). External radiator heaters were used separately at first and then with TISA heaters. During this heating period, one cool-down of the system to 130°C (403 K) occurred to permit repair of a Baikal test stand subsystem. An emergency cool-down occurred on September 30, 1988, caused by the NaK leak in the lower radiator manifold. Following the manifold repair, the system was charged with NaK and heated twice by the radiator heaters to 550°C (823 K).

During the period from March 3 to April 7, 1989, the NaK coolant was purified, the system out-gassed, and the cesium system adjusted. System temperatures were varied from 300 to 550°C (573 to 823 K). On April 7, Ya-21U was shut down for sealing of the cesium evacuation system. The sealing of the cesium system was completed on April 19, 1989.

From May 17 to June 13, 1989, system parameters were measured at TISA power levels of 20, 40, and 60 kW. Four cool-downs occurred during this period from temperatures of 300°C (573 K), 350°C (623 K), 450°C (723 K), and 275°C (548 K). Two of the cool-downs were caused by external power supply losses, while the other two were caused by misalignment of the work section voltage symmetry. The Baikal test stand vacuum chamber was opened to inspect and correct the system. It was determined that an electrical contact existed between a cesium unit thermal conducting bar and a work section terminal at the lower end of the reactor section. Elimination of the electrical contact corrected the work section voltage misalignment problem.

On June 13, 1989, Ya-21U was operated at a TISA heater power level of ~74.5 kW. Helium was then evacuated from the cesium system and the work section voltage set at 29 V. At a TISA heater power level of 76 kW, the work section current was 72 A. This was followed by a test at a level of 73 kW while the cesium pressure settings were varied. A similar test was performed to determine the optimum cesium pressure setting at a TISA heater power level of 85 kW. The results of the optimum cesium pressure test are illustrated by Figure 24.

Based on the ratio of cesium pressure to maximum work section power output, a cesium pressure setting of 1.6 torr was established for the Ya-21U system for a work section power output of 5 kWe. Ya-21U system characteristics and parameters for a cesium pressure setting of 1.6 torr were also determined.

During the above period, the automatic control drive and position sensor were checked for proper operation and sensor calibration. Samples of NaK coolant were obtained from the Ya-21U NaK system at several intervals to determine the presence and concentration of oxygen and hydrogen in the coolant. On July 15, 1989, Ya-21U was cooled to ambient and shutdown.

During the thermal vacuum control and acceptance tests, Ya-21U experienced nine cool-downs from 270-550°C to 30-50°C (543-823 K to 303-323 K). Two power reductions occurred, one during a TISA heater shutdown and the other during a switch-over from the radiator electric heaters to the TISA heaters.

The control testing of Ya-21U was completed and cool-down was conducted on July 15, 1989. The measured results of the Ya-21U thermal vacuum tests are indicated in Table 7 and TFE potentials in Table 8. Table 9 lists the system cool-downs and causes.

2.4.2 Thermal Vacuum Acceptance Tests

Acceptance tests of Ya-21U were performed during the period from August 8 to 14, 1989. The acceptance tests included a normal heatup rate and operation at the established mode for non-nuclear tests and a rapid startup from a TISA heater power level of 2.5 kW to a TISA power of 83.5 kW within a 23-min period, as illustrated by Figure 25. Ya-21U system parameters at conclusion of the rapid startup are listed in Table 10.

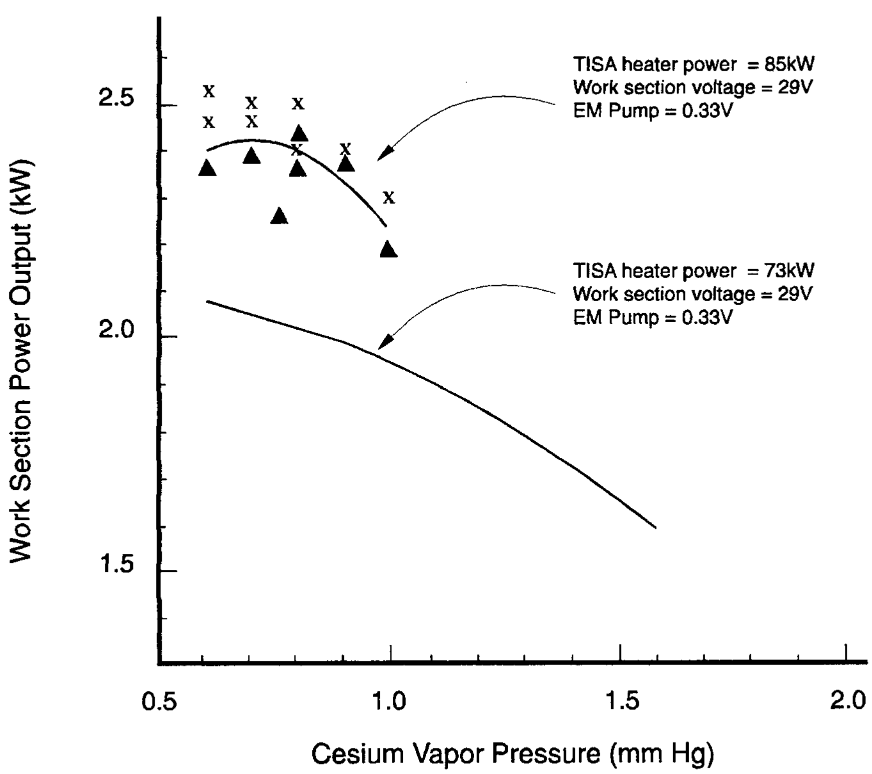


Figure 24. Ya-21U working section power versus cesium vapor pressure.

Table 7. Ya-21U system parameter data during control tests.

Parameter	Units	Value	Value	Value
TISA Heater Power	kW	73	85.1	84.7
Cesium Vapor Pressure	torr	0.6	0.7	1.6
System Temperature (21.07)	°C	465		495
Work Section Current	A	72	82.4	66
Work Section Voltage	V	29	29	28.5
Work Section Power	kWe	2.09	2.39	1.89
EM Pump Section Voltage	V	0.47	0.48	0.48
EM Pump Make-up Current	A	173	175	250
EM Pump Voltage	V	0.33	0.32	0.33

Table 8. Potential distribution of Ya-21U TFEs.

System Test Parameters	TISA Power 73 kWe & Cesium Press 0.6 torr	TISA Power 85 kWe & Cesium Press 0.7 torr		TISA Power 73 kWe & Cesium Press 0.6 torr	TISA Power 85 kWe & Cesium Press 0.7 torr
TFE #	Potential Volts	Potential Volts	TFE #	Potential Volts	Potential Volts
28	0.86	0.83	21	0.84	>1.0
27	0.78	0.76	20	0.84	0.83
26	0.92	0.86	19	0.63	0.75
25	0.91	0.82	18	0.70	0.78
24	0.93	0.87	17	0.91	0.83
23	0.63	0.73	16	0.88	0.83
22	>1.0	0.89	15	0.69	0.77
11	0.64	0.69	14	>1.0	>1.0
10	0.80	0.79	13	0.90	0.82
7	0.86	0.90	12	0.96	0.88
6	>1.0	0.92	34	>1.0	>1.0
5	>1.0	0.93	33	0.89	0.83
4	0.85	0.79	32	0.78	0.91
3	0.80	0.84	31	0.73	0.75
8	0.93	0.87	30	0.66	0.76
2	0.76	0.76	29	0.97	0.92
1	0.96	0.85	PS*	0.47	0.48
9	>1.0	>1.0			

* PS = EM Pump Section

Table 9. List of Ya-21U system cool-downs and causes.

Date	Test Stage	Heat Source	TISA Power kWe	T_{max} °C	T_{min} °C	Cause
9-21-88	CT	TISA & REH	12 49	480	300	TISA shutdown
9-30-88	CT	REH	52	550	40	Automatic after signal, "REH overload"
11-23-88	Leak search	REH	52	550	50	Technical decision after signal, "R_{inc} not enough"
12-21-88	Leak search	REH	52	520	50	Emergency cool-down after signal, "Leak"
3-22-89	CT	REH	52	550	325	Switch from REH to TISA
4-9-89	CT	REH	52	560	40	Planned cool-down
5-20-89	CT	REH	13	300	50	Emergency cool-down, power loss
5-30-89	CT	TISA	40	350	50	Technical decision
6-01-89	CT	TISA	55	460	25	Technical decision
6-11-89	CT	TISA	?	275	30	Self cool-down after signal, "Circuit blinking"
7-15-89	CT	TISA	83	500	50	Planned
8-17-89		TISA	83	500	50	Automatic after signal, "Circuit blinking"
10-5-89		TISA	86	525	50	Operations on B-3 rig
11-3-89		TISA	40	380	50	Preventive operations on B-3 rig
11-28-89		TISA	83	500	50	Automatic after TISA shutdown
12-13-89		TISA	83	500	40	Emergency cool-down after signal, "Circuit blinking
3-5-90	HPT	TISA	82	450	40	Technical decision for load switch
3-18-90	HPT	TISA	86	450	50	Emergency cool-down after signal, "Circuit blinking
4-4-90	HPT	TISA	123	55	450	End of high power mode
4-5-90	HPT	TISA	86	450	50	End of testing

NOTE: CT = control test
REH = radiator electric heater
Circuit Blinking = alarm light flashing
B-3 = Baikal test stand
HPT = High-power test

2.4.3 Additional Thermal Vacuum Tests

After completion of the acceptance tests, additional thermal vacuum tests were conducted to confirm the performance and workability of Ya-21U and its NaK coolant system for future power tests. The test objectives and results were:

1. Perform work section power optimization tests at the cesium pressure established during the acceptance test at a TISA power level of 86 kW.
2. Determine optimum cesium pressure at work section voltages from 15 to 34 V.
3. Set the steady-state work section voltage at 29 ±0.5 V.
4. Determine optimum Ya-21U system performance and characteristics at the end of every 500-hr period of operation as indicated by Table 11.

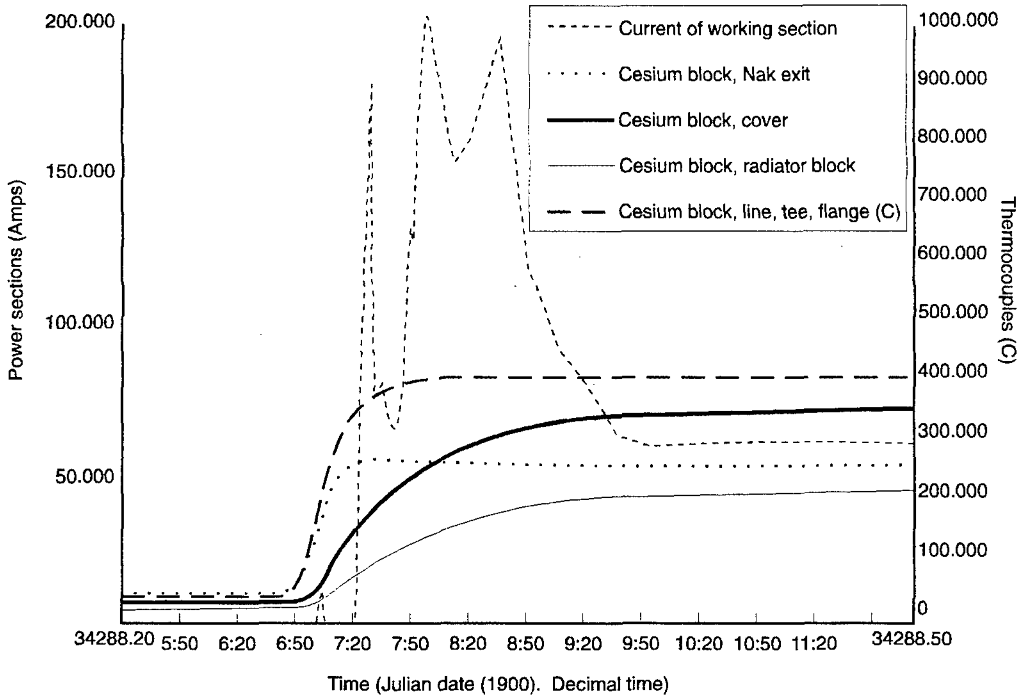


Figure 25. Ya-21U rapid startup parameter profiles.

Table 10. Ya-21U parameters following rapid startup.

Parameter	Units	Value
TISA Heater Power	kW	83.5
Cesium Vapor Pressure	torr	0.9
System Temperature (21.07)	°C	490
Work Section Current	A	78
Work Section Voltage	V	29
Work Section Power	kWe	2.26
EM Pump Section Voltage	V	0.48
EM Pump Make-up Current	A	210
EM Pump Voltage	V	0.33

Table 11. Ya-21U system performance at 500-hr intervals.

Test Period	TISA Power, kW	Work Section Power, kWe	Optimum Cesium Pressure, torr
8-15 to 8-16	86	2.52	0.6
9-1 to 9-4	85.7	2.46	0.7
9-26 to 9-28	86	2.32	0.7
11-23 to 11-24	86	2.39	0.7

Five tests of Ya-21U were completed. At that time, Ya-21U had operated 2,100 hr at temperatures above 160°C (433 K); 1,800 hr above 350°C (623 K); and 1,710 hr above 450°C (723 K). The work section produced more than 2 kWe for a period of 1,680 hr. The Ya-21U system, NaK coolant system, and new TFEs had operated without fault for a significant period of time and provided ample data on optimal characteristics.

2.4.4 High Power Thermal Vacuum Tests

A decision was made in early February 1990 to perform high-power thermal vacuum tests on Ya-21U. The purpose of the tests was to determine the workability and performance of Ya-21U when the work section was producing 5 kWe at the work section terminals. Tests were performed in Baikal test stand #3 between February 16 and April 5, 1990.

Test preparations included outgassing and operation to characterize the system. Optimal cesium pressure settings were determined for a TISA power level of 82.1 kW. NaK coolant samples were taken and analyzed. The system was then cooled down to permit adjustment of the work section load for a power output of 5 kWe.

High-power tests were performed from March 7 to April 6, 1990. TISA heater power was increased and stabilized at 20, 40, 60, and 85.5 kW to permit measurement of Ya-21U's characteristics. TISA heater power was then raised to 123 kW, and the work section power output versus cesium vapor pressure was determined for cesium pressure settings between 0.6 and 2.0 torr. Voltage-current characteristics were also determined at the optimum cesium pressure setting of 0.6 torr for work section voltages between 20 and 30 V, as indicated by Table 12 and Figure 26. The system parameters before and after the high power test are indicated by Table 13. Ya-21U's TFE potential distribution was determined and compared at a TISA heater power levels of 123 kW and 85.6 kW, as indicated by Table 14.

Table 12. Ya-21U voltage-current characteristics at 123 kW TISA power level.

Work Section Voltage -V	Work Section Current -A	Work Section Power -kW
30	165	4.94
29.3	168	4.92
28	174	4.88
27.1	179	4.86
26	187	4.87
25	190	4.75
24	198	4.76
23	201.5	4.63
22	210	4.61
21	216	4.53
20	225	4.50

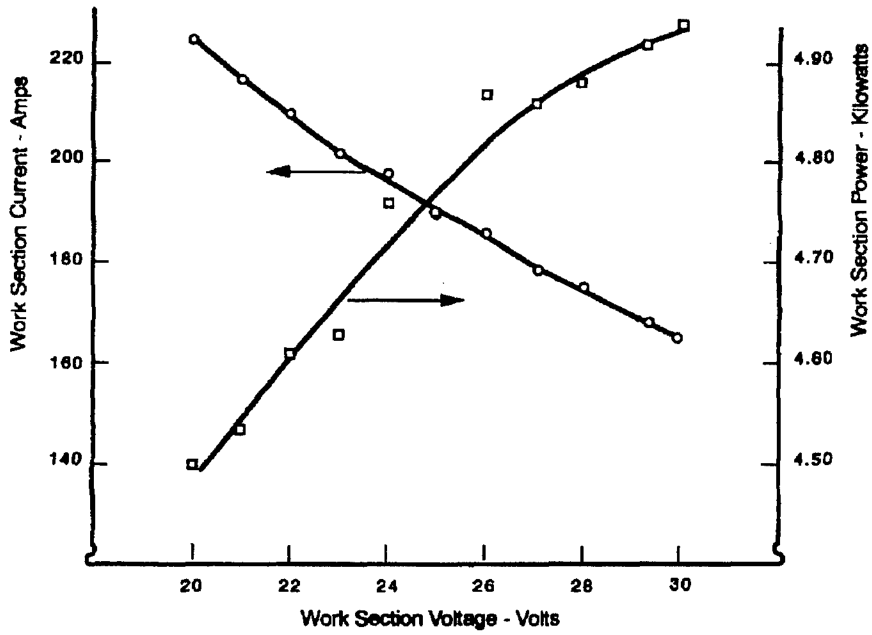


Figure 26. Ya-21U voltage-current characteristics at 123-kW TISA power level.

Table 13. Ya-21U system parameters before and after high-power tests.

Parameter	Units	Value	Value	Value
TISA Heater Power	kW	85.9	123	85.6
Cesium Vapor Pressure	torr	0.6	0.6	0.6
System Temperature (21.07)	°C	460	534	455
Work Section Current	A	80.8	174	80
Work Section Voltage	V	27.3	28.9	27
Work Section Power	kWe	2.2	5.02	2.16
EM Pump Section Voltage	V	0.47	0.57	0.47
EM Pump Make-up Current	A	300	0	280
EM Pump Voltage	V	0.33	0.36	0.33

During the performance of the high-power thermal vacuum tests, Ya-21U received three thermal cycles. The system operation at temperature was as follows:

840 hr at temperatures above 100°C (373 K)
650 hr at temperatures above 350°C (623 K)
300 hr at temperatures above 450°C (723 K)
150 hr at work section power generating mode
45 hr at work section power generation of 5 kWe

System performance characteristics obtained during the Ya-21U high-power thermal vacuum tests is illustrated by Figure 27. System temperature histograms for Ya-21U are illustrated by Figures 28 and 29.

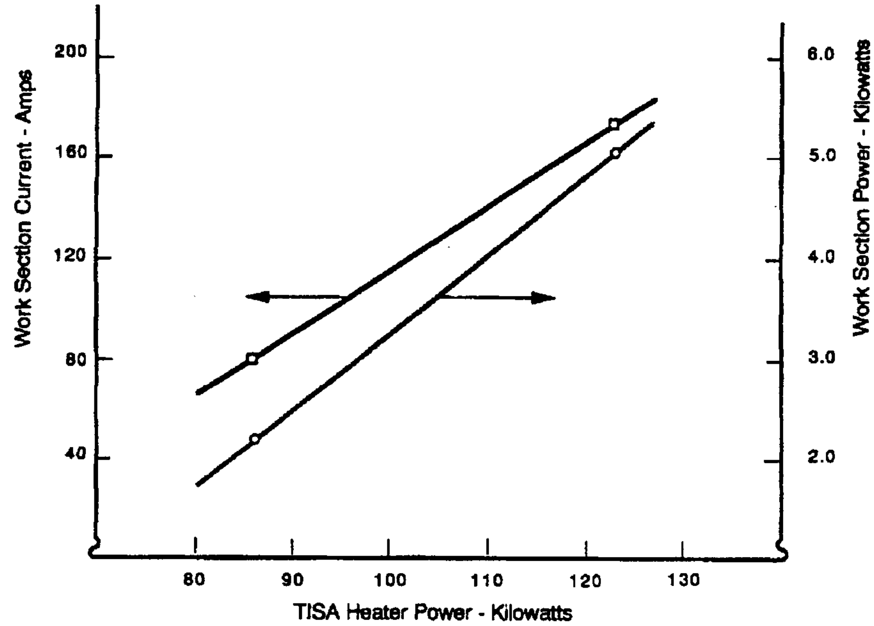
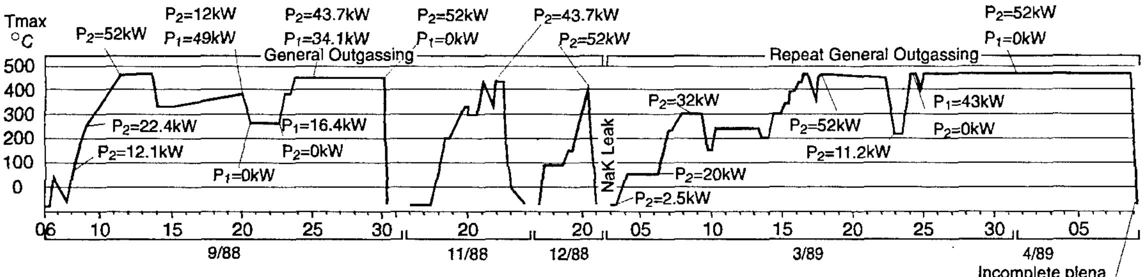


Figure 27. Ya-21U work section power versus TISA heater power during high-power tests.

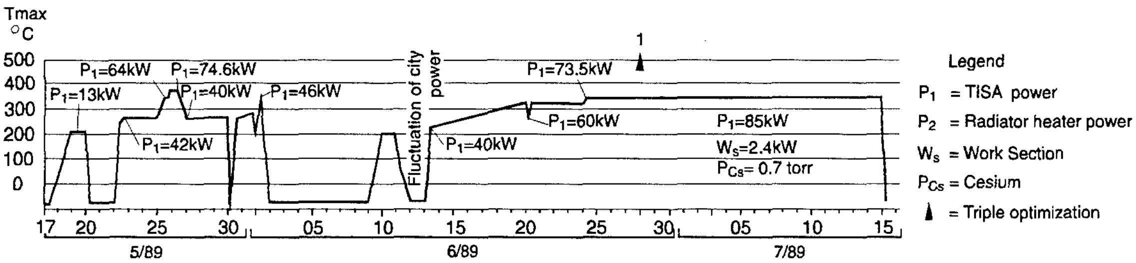
Table 14. Ya-21U TFE potential distribution during high-power tests.

System Test Parameters	TISA Power 123 kW & Cesium Press 0.6 torr	TISA Power 85.6 kW & Cesium Press 0.6 torr		TISA Power 123 kW & Cesium Press 0.6 torr	TISA Power 85.6 kW & Cesium Press 0.6 torr
TFE #	Potential Volts	Potential Volts	TFE #	Potential Volts	Potential Volts
28	>1.0	0.97	21	0.94	0.90
27	0.31	0.27	20	0.80	0.78
26	>1.0	>1.0	19	0.78	0.69
25	0.85	0.77	18	0.78	0.70
24	0.93	0.81	17	0.81	0.74
23	0.82	0.70	16	0.85	0.82
22	0.96	0.86	15	0.77	0.73
11	0.79	0.66	14	0.94	>1.0
10	0.90	0.80	13	0.82	0.80
7	0.98	0.88	12	0.90	0.87
6	0.93	0.89	34	0.94	0.92
5	0.91	0.88	33	0.82	0.80
4	0.80	0.72	32	0.85	0.82
3	0.86	0.80	31	0.75	0.69
8	0.84	0.78	30	0.72	0.66
2	0.76	0.68	29	0.86	0.82
1	0.94	0.78	PS*	0.57	0.47
9	0.93	0.91			

- PS = EM pump section TFE voltage

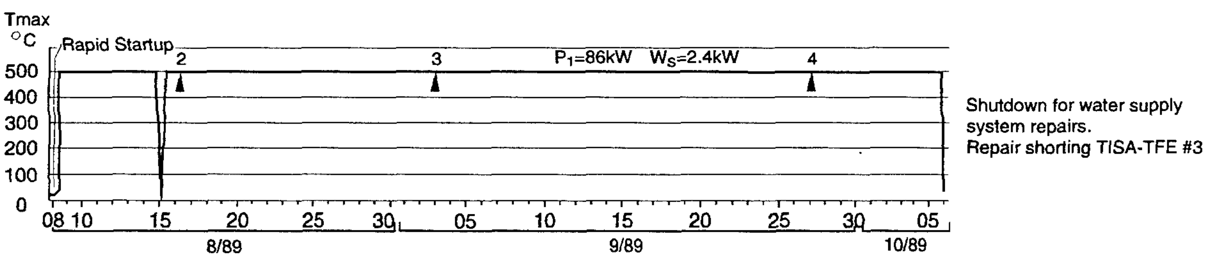


(a) General outgassing and repeat of general outgassing and plena treatment.

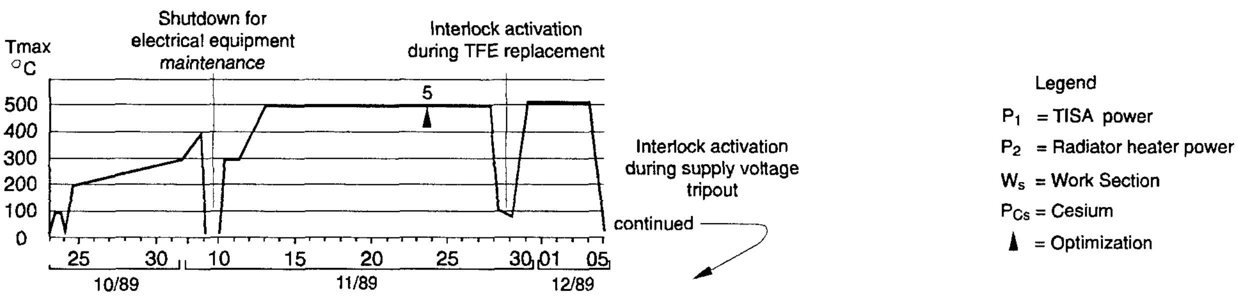


(b) Parameter checks after plena sealing.

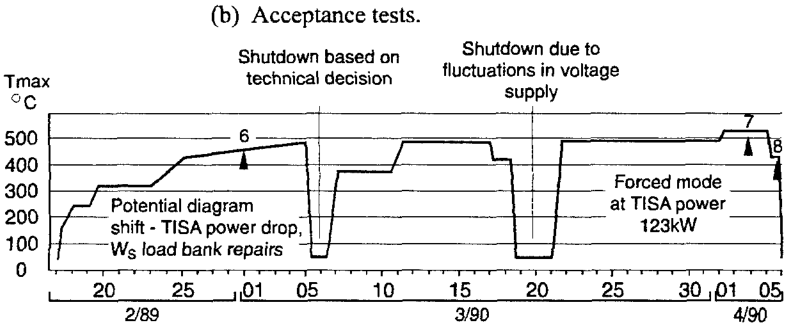
Figure 28. Ya-21U system test temperature histograms.



(a) Acceptance tests.



(b) Acceptance tests.



(c) Additional tests based on technical decision, without skirt.

Figure 29. Ya-21U system acceptance test temperature histograms.

2.5 NAK COOLANT SYSTEM STATUS

Ya-21U was tested and re-tested in a thermal vacuum environment in Russia after system assembly and before delivery to TSET, Albuquerque, NM. Re-testing was required because the material and process used for fabrication of the radiator collectors and radiator tubes were inadequate and were the primary cause of NaK leaks during high temperature thermal vacuum tests (Ogloblin, #17).

The correction of each NaK leak required drainage of the NaK coolant system, repair of the leak, refilling and cleanup of the NaK system, and demonstration by re-testing that the leaks were corrected. The repair of each leak exposed the NaK wetted system to some contamination from in-leakage of air, especially oxygen. This could have caused system problems; for example:

1. Low concentrations of oxygen in the NaK coolant could cause oxide films to form on the interior surfaces of the NaK system. These oxides when dissolved at higher system temperatures could then form oxide precipitates when cooled to ambient temperatures.
2. If the total inventory of oxides was precipitated at the coldest point in the NaK system, NaK flow could be restricted; i.e., plugging of radiator tubes.
3. Depending on the coolant flow and temperature, an increased presence of oxygen in the NaK coolant could increase the corrosion rate of the austenitic stainless steel and cause NaK system failure during extended, long-duration tests at high temperature.

It was considered essential to determine the current oxygen concentration in the Ya-21U NaK system before the start of the thermal vacuum tests and to compare this concentration with the specific system requirements (NaK oxide limit of 5-10 ppm). The evaluation performed and reported by Russian specialists determined that the initial oxide concentration of the Ya-21U NaK coolant following final repair and refilling could be as high as 2,000 ppm.

After 72 hr of purification by cold trapping, the oxygen concentration calculated by Russian specialists would be reduced to ~50 ppm. Analyses were made and are listed in Table 15.

2.6 SYSTEM STORAGE AND SHIPPING

In July 1990, Ya-21U was disconnected from the Baikal test stand and installed under protective cover in the high-bay area at CDBMB, St. Petersburg, Russia until April 1992 . In April 1992, preparations were made to send Ya-21U to the U.S.

The preparations included disassembly of loads and some elements of the guides for ejection of the thermal shield in accordance with *Technical Decision on Ya-21U Modification, #4-107/16-91; 01-23-91.* Electrical checks were performed and the Ya-21U gas systems were inspected in accordance with *Technical Decision on Electrical Checks and Gas System Inspection of Ya-21U, #2-106/16-91; 01-17-91.*

Table 15. Results of NaK sample analysis.

Date	Ya-21U Temp °C	Oxygen Content %	Hydrogen Content %	Notes
9-21-88	440	*	*	No results--sampler failure.
3-17-89	450	4.5×10^{-3}	$<1.0 \times 10^{-4}$	NaK sample corresponds to item 8.5 from 182-01-0021PM.
3-23-89	317	8.0×10^{-4}	$<1.0 \times 10^{-4}$	Oxygen content does not correspond to 182-01-1408TU.
3-30-89	550	*	1.0×10^{-4}	Oxygen content does not correspond to 182-01-1408TU.
7-5-89	500	4.8×10^{-4}	$<5.0 \times 10^{-3}$	Corresponds to 182-01-1408TU requirements. Hard particles remained after evaporation of sample.
2-6-90	15	*	*	Presence of Fe, Ni, and Cr from stainless steel. Sampler at fault.

- = data were not obtained
- Russian specialists also determined, by calculation, that the corrosive effects of the current oxide concentration on the structural materials (austinetic stainless steel used for construction of the NaK system) would not alter the serviceability of the Ya-21 system. Based on previous Ya-21U test results obtained by Russian specialists, experimental tests of 1,000 hr in duration at temperatures above 450°C (723 K) were planned to demonstrate the integrity of the NaK system and components.

The internal cavities of the TFEs were cleaned and inspected for dimensional variances by insertion of a dimensional (go-no-go) gauge into the cavities in accordance with *Technical Decision on Reactor TFE Internal Cavities Preparations, #6-105/16-91; 01-25-91.*

The system isolation was completed in accordance with *Technical Conditions on Reactor Unit, 182-01-0021TU2.* Cables were secured according to drawings 182-68-0021 SB without the installation and use of cross braces. Before Ya-21U was installed in the transportation device, pipeline 182-24-0165 was secured to the support structure, and the radiator and shield were covered with plastic. Preparations for shipment of the Ya-21U system were then completed.

In May 1992, Ya-21U was loaded into a TOPAZ-II shipping container and delivered by a U.S. Air Force C-5A aircraft to Albuquerque, NM.

2.7 LESSONS LEARNED

Details of the process used for manufacturing and acceptance of Ya-21U prior to its delivery to the TSET Lab were difficult to obtain. Because of this, many questions about the quality and reliability of the assembled system were raised.

The lessons learned while exploring the heritage of Ya-21U, system manufacturing, the Baikal test stand thermal vacuum tests, and NaK coolant system leaks were applicable to the future testing and evaluation of TOPAZ-II systems, EH-43 and EH-44.

2.7.1 Russian Quality Assurance

The TOPAZ-II manufacturers developed design documentation that permitted fabrication of the systems to be performed at three enterprises using three separate specifications. The specifications were as follows:

182-01-0021TU1:	The reactor unit (RU) was manufactured without loading of the cavities with working media (gases, cesium, NaK). An acceptance protocol was produced after manufacturing that stated the deviations from the specification.
182-01-0021TU2:	The complete RU set was fabricated (except for nuclear fuel); the cavities were loaded with working media; thermal and electrical characteristics and mechanical functioning were checked; and a certificate was produced to indicate results for each of the delivered units.
182-01-0021TU:	Nuclear fuel was loaded; cold neutronic startup was carried out; results were entered in the certificate; and a final report on system preparation for delivery was produced for each system.

Russian quality assurance procedures were the same for all manufacturers. For example, the TOPAZ-II systems Ya-21U, EH-41, EH-43, and EH-44 were fabricated by the manufacturer in accordance with the design documentation (DD) produced by CDBMB and technological documentation (TD) developed in accordance with the DD. The complete set of DD and TD defined all requirements for the checkout and manufacturing of the assembly elements and systems and the performance of their acceptance tests.

The quality of both DD and TD was assured by the manufacturing and testing results of assembly elements and reactor unit (RU) experimental prototypes and by results of Russian operational tests. A change control system was developed for tracking each deviation from the DD by using a DD change log and permit card (PC). The DD requirements, type of deviation, reason for a deviation, and measures for elimination of the reasons for the deviation were indicated on the PC. Based on an analysis of repeatability of deviations, their reasons, necessary corrective measures, and the effectiveness of new measures, specific DD and TD changes would be introduced. Information on approved changes during manufacturing of each RU and its assembly elements was accumulated for subsequent quality analysis and summary presentation.

The specialists of the CDBMB Technical Control Division (TCD) and a customer representative (CR) carried out all aspects of control. The TCD carried out all operations at all manufacturing stages and maintained periodic control of equipment in accordance with their warranty information. A CR provided the quality control of the parts, assembly units, and systems according to the quality control list. The CR provided transitory quality control of operations not specified by the quality control list. The fabrication quality control of parts, assembly elements, and systems included the following in detail:

- Presence and completeness of accompanying documentation;
- Presence and completeness of Certificates for Materials from which parts were made;
- Control, observance, and compliance with technical disciplines;
- Checkout of compliance of a part or assembly unit with the DD requirement;
- Checkout of the technological process and operations fulfillment;
- Availability and use of serviceable measuring devices, instruments, rigs, and technological equipment for fabrication of parts and assembly units that passed periodic calibration and had traceable records;
- Presence of skilled worker qualification certificates permitting operations with the systems, welding, and other operations;
- Classification of welding operations used during welder certification;
- Quality control of welding joints;
- Order for admittance of welders to the certification;
- Documentation presenting the result of certification;
- Observance of safety procedures during fabrication and control;
- Special quality control procedures;
- Set integrity according to technology specification requirements.

Ya-21U (factory number 19) was fabricated on December 29, 1987. It complied with the requirements 182-01-0021-02 (change 127) and 182-01-0021TU1 (change 107). This system was accepted for further operations according to 182-01-0021TU2 with consideration of changes indicated in the Summarized Record of Approved Deviations. Ya-21U was delivered with accompanying documents; a system passport and a manufacturer's acceptance certificate.

After some time had passed, the following information related to the Russian quality assurance programs was acknowledged by TSET personnel and management:

- Russian specialists used a set of tiered documents to define technical specifications, assembly, testing, and acceptance and what to do in case deviations were determined.
- Russian quality assurance records were clear and traceable.
- Russian welders were certified according to special requirements. Original certification documents were maintained for systems and showed the process followed.
- Russian packaging and transportation of subsystems and systems was controlled and documented.
- All changes to the systems and subsystems were clearly delineated with supporting documents and could be traced easily. All deviations from master documents were documented and reviewed to determine effects of individual deviations and accumulated effect.
- All incoming system inspection certificates were formatted analogously to acceptance protocols.
- Some documents used during fabrication and assembly by Estonia may be unavailable or missing as a result of the breakup of the Former Soviet Union.

Ya-21U was delivered with an accompanying passport that contained historical information and the manufacturer's acceptance certificate (Ogloblin #17).

2.7.2 Access and Use of Russian Technical Documents

Russian technology was transferred to the TSET Program by technical documents, oral communications, on-the-job interactions between technical personnel, and during performance of system tests. In accordance with approved contracts, many technical documents were delivered, but only high priority documents were translated.

Documents needed to support TSET activities required translation and took considerable time and effort to translate. Other documents were unavailable when the information was needed due to translation priorities and lack of knowledge of document contents. Also, many useful technical documents, not included in the contract deliverables, were possessed and used by Russian specialists during their active participation in the TSET activities. The existence and usefulness of these documents became known whenever unanticipated technical problems occurred or when more detailed technical issues were discussed and additional supporting information was required to understand system characteristics.

In addition, the accuracy, readability, and technical content of translated Russian documents must be monitored and checked to assure quality of translations and translated documents are consistent with the non-translated original documents. This quality check is very important and must be performed in a timely expeditious manner because: (1) some Russian to English translators may not be professionally trained, familiar with the technology, equally skilled, and motivated; (2) slight variations in translated text of technical documents caused confusion, misunderstanding, and unproductive use of highly skilled U.S. and Russian specialists to resolve; and (3) poorly translated technical documents that have been widely distributed for use were difficult to recall, revise, and re-issue after the original translator was assigned to other duties.

Accordingly, selection, purchase, delivery, and translation of technical documents to support technology transfer should be determined early in the program and be based on the need for that information and its timeliness. The hierarchy of technology to be transferred, identification of technical documents containing that technology, document delivery schedules, priorities for translation, and quality of the translated documents must be consistent with overall program requirements, schedules, and funding resources.

3.0 SYSTEM TEST PREPARATIONS

3.1 INTRODUCTION

Preparations for one modal, 13 thermal vacuum tests, and one mechanical test of Ya-21U provided many opportunities to become familiar with the TOPAZ-II system design, thermionic system technology, and techniques required to evaluate an integrated space power system's performance.

Immediately after delivery of the shipping container and Ya-21U to TSET, a concern was raised that related to the potential contamination of the reactor by beryllium dust particles may have been mobilized during transportation between Russian and TSET laboratory. This concern prompted a rigorous inspection and sampling of the system by the Lovelace Inhalation and Toxicology Research Institute as it was removed from its shipping container.

Only trace amounts (less than the minimum standard for surface/air contamination levels) of beryllium dust were found, which posed no hazard to operation personnel. Thereafter, standard industrial hygiene practices were used to clean and monitor Ya-21U prior to further inspections and functional testing.

Visual inspections of Ya-21U were then performed according to Russian procedures used previously *(1515-01-0001 PM1)*. Except for a few additions, results of visual inspections performed at the TSET laboratory coincided with those obtained by Russian specialists. Ambient functional and electrical tests of Ya-21U were performed thereafter and also compared with tests performed in Russia.

After completion of the ambient functional and electrical tests, Ya-21U was prepared for modal testing in the highbay of the TSET laboratory. The modal test was required to obtain structural response data for correlation with a finite element model being developed for use during subsequent mechanical testing and evaluation of the system's structural components.

Preparations for the first thermal vacuum test of Ya-21U began in May 1993. and were completed during concurrent performance of the Ya-21U modal tests. (Note: The same Baikal thermal vacuum chamber and auxiliary systems used previously in Russia to test Ya-21U as well as other TOPAZ II systems were installed in the TSET laboratory. Details of the Baikal test stand are contained in Section 7.)

Test preparations for the first thermal vacuum test of Ya-21U included: modification, installation, and connection of the cesium vapor evacuation piping; installation and connection of electrical wiring for operation of the cesium block puncture valve to permit evacuation of the interelectrode gaps of the TFEs; attachment of additional temperature sensors to determine temperature profiles of selected Ya-21U subsystems and components during the experimental tests; and fabrication and installation of a thermal shield around the lower section of the system radiator to increase NaK system temperatures and reduce TISA heater power requirements.

Based on previous Russian results and specialists' recommendations, preparations were made to perform experimental tests of 1000 hr duration at temperatures above 450°C (723 K). Baikal test stand systems were pre-tested and calibrated in accordance with Russian procedures. Shortly thereafter, Ya-21U was installed, secured to the vacuum chamber, connected to Baikal test stand interface connectors, and instrumented with additional temperature sensors for the special experiments.

Heat sinks were installed to cool Ya-21U pressure sensors, automatic control drum drive, and interface connectors. A thermal shield was placed around the radiator's lower section to increase NaK system operating temperatures and/or to reduced TISA heater power levels. The cesium system evacuation line was connected to the cesium block vapor vent line, using special puncture valve fittings, and then out-gassed and leak checked.

Mid-sections of the Baikal test stand chamber were installed; cesium vapor throttle valve linkage connected, TFE voltage taps connected, and TISA heaters inserted in TFE emitter cavities. TISA heater cables were then connected to heater leads and vacuum chamber feed-throughs. Thereafter, the large turbomolecular pumps, gate valves and top cover were installed and secured and the remainder of the auxiliary systems prepared for system test operations.

After completion of thermal vacuum tests #1 through #8, Ya-21U was de-coupled from the Baikal test stand interface connections and prepared for vibration and shock tests at the Sandia Laboratories mechanical test facility. Small cylindrical caps were fabricated and attached temporarily to the top of the reactor plenum to seal off the small leaks observed in TFEs during the previous thermal vacuum tests.

Special procedures and fixtures provided with the Baikal test stand were used to pinch and seal the cesium evacuation line, prevent inleakage of air, and permit reconnection after completion of the mechanical tests. Functional and electrical tests were performed and results compared with previous pre-thermal vacuum tests.

Calibrated tri-axial accelerometers were secured to designated Ya-21U components prior to placement of the system in the shipping container for delivery to the mechanical test facility. Portable shock monitors were attached to Ya-21U and its shipping container to record shocks received during transportation and handling between TSET and Sandia National Laboratory (SNL) facilities.

After arrival at the mechanical test facility, Ya-21U was removed from the shipping container, rotated to the vertical position, placed on the test fixture and secured. The tri-axial accelerometers were connected to control and data acquisition systems and circuits checked for functional response.

Following completion of the mechanical tests, accelerometers were disconnected and system detached from the fixture, placed in shipping container, and returned to the TSET facility for detailed post test inspections, leak checks, and functional tests.

Post-test leak checks and inspections revealed a new leak in a weld on a cesium vapor exhaust line and an increase in leak rate and number of leaking TFEs. An attempt was made to correct the new leak during preparations for final thermal vacuum testing of Ya-21U. Physical inspections also revealed that one of the six reactor support fasteners had loosened during the mechanical tests.

All accelerometers were removed from Ya-21U prior to reconnection of the Baikal test stand interface connections. The remainder of the preparations for final thermal vacuum performance testing were similar to the previous thermal vacuum test preparations.

Lessons learned during preparation for modal, thermal vacuum, and mechanical testing of Ya-21U are provided in subsequent paragraphs of this Section.

3.2 DELIVERY AND INSPECTION

Ya-21U was inspected at the Russian facility of the Central Design Bureau for Machine Building (CDBMB), prepared for shipment and installed in a shipping container filled with argon and sealed. Some time thereafter, the container was moved to the airfield tarmac at St. Petersburg, Russia, and loaded into a U S Air Force C-5A military cargo airplane. One day later, the C-5A delivered the container and other equipment to the TSET laboratory, Albuquerque, NM. After arrival at Albuquerque, the shipping container was off-loaded from the C-5A transport airplane and placed in temporary storage.

3.2.1 Beryllium Inspection

Concurrent with the thermal vacuum testing of the TOPAZ-II V-71 system, Ya-21U was moved to the high bay of the TSET laboratory. Air temperature, atmospheric pressure, humidity and dust levels were monitored and deemed acceptable. Following this, Ya-21U was slowly removed from the shipping container. Beryllium smears were taken to determine levels of concentration from the reactor, radiation shield, structure, strong-back handling fixture, and internal surfaces of the container during removal of Ya-21U, as illustrated by Figure 30, prior to visual inspection and functional checkout. Trace amounts of beryllium dust were found, analyzed, and determined to be no hazard to operation personnel. Thereafter, standard industrial hygiene practices were used to clean and monitor Ya-21U prior to further inspections and functional testing. Approvals were given to proceed with the visual inspections and functional checkout (Hoover #18).

3.2.2 Visual Inspections

Visual inspections of Ya-21U were performed according to procedure 1515-01-0001 PM1. Hermetic seals and piping of the NaK system, cesium system, and gas systems were inspected to detect possible damage during shipment. Outer surfaces were inspected visually for detection of damage, corrosion, and signs of NaK leaks.

Piping, cable, and electrical shunts were checked by hand for movement to determine proper attachment and support. The thermal insulation, reactor cable assemblies, ceramic insulators, reflector bands, and fusible links were visually inspected to determine condition and status.

The internal surface of the cavity within each TFE was inspected for cleanliness by insertion of a dry tampon of bleached cambric fiber. The internal geometry of each TFE cavity was checked by insertion of a go-no-go gauge to determine internal alignment and symmetry of the TFE emitter.

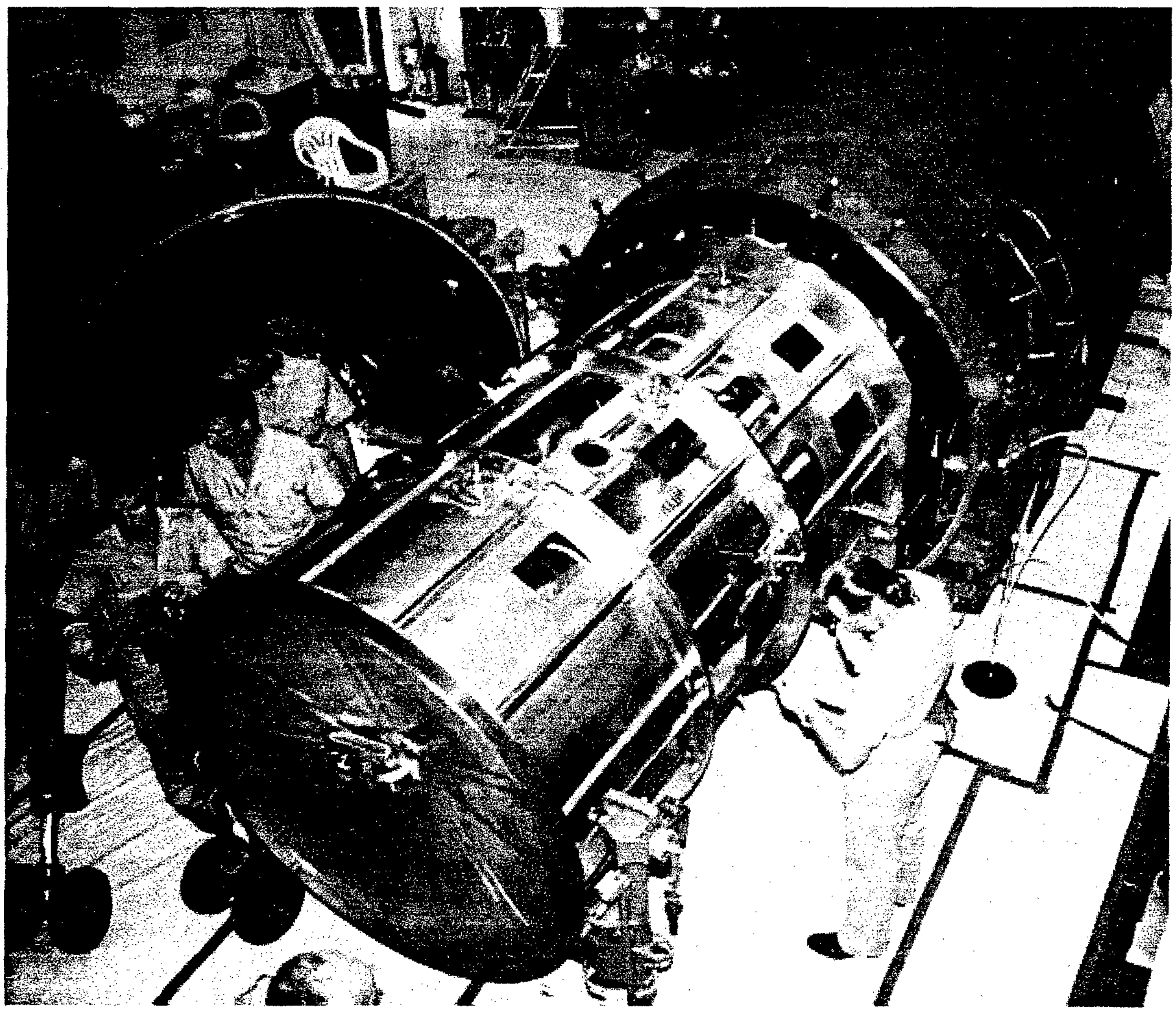


Figure 30. Inspection of Ya-21U for beryllium contamination.

The results of the visual inspections performed at the TSET laboratory coincided with results obtained previously and reported by Russian specialists, with the following additions:

1. Three safety rod drives were installed on Ya-21U.
2. A lock-washer that secures the lower collector to the chassis (near the NaK return line) was missing.
3. Two locking devices on the cable on the upper collector and three locking devices on the attachment of cables of the startup unit simulator were missing.
4. Surfaces of the control rod drive shield had an oxide film on them.
5. Blemishes were seen on the surfaces of the control rod covers.
6. The screw locking device that attaches the thermal resistance under the startup unit was missing.
7. A screw locking device on a collar, on the upper radiator collector, that secures a cesium vapor line was broken.
8. The exposed surfaces of Ya-21U were dusty and required cleaning by vacuum and with alcohol soaked pads.

3.2.3 Document Inspections

Documents that accompanied the delivery of Ya-21U were examined to determine translation status, type, content, application, and priority for use. Some documents had been translated previously by Russian translators and were provided in both Russian and English. Other Ya-21U documents were provided in Russian and required extensive translation before use. An important consideration during the examination was whether information provided in the documents could be used to fulfill technical requirements related specifically to the testing guidelines provided by MIL-STD-1540B.

3.2.4 NaK Coolant System Integrity

A detailed visual inspection of the Ya-21U NaK system piping and components was performed to identify the presence of NaK oxides, if any. This was done because NaK leaks did occur during Russian high-temperature, thermal vacuum tests of TOPAZ-II systems and were thought to be related to the materials and processes used for fabrication of the radiator collectors and tubes. Ya-21U was fabricated using similar materials and had similar leaks which were repaired in Russia during manufacturing and acceptance testing.

Accordingly, the integrity of the NaK system on Ya-21U was uncertain because the repair of each leak exposed the NaK wetted system to contamination from in-leakage of air, especially oxygen. This contamination could cause system problems; for example: (1) oxides could form on the interior surfaces of the NaK system when low concentrations of oxygen are present in the NaK coolant. These oxides would be dissolved at higher system temperatures and could form oxide precipitates when cooled to ambient temperatures. (2) NaK flow could be restricted (or plugging could occur in the radiator tubes) if the total inventory of oxides are precipitated in the coldest regions of the NaK system. (3) Also, the corrosion rate of the austenitic stainless steel would be increased with higher concentrations of oxygen in the NaK coolant. Depending on the

coolant flow and temperature, higher concentrations of oxygen in the NaK coolant could cause system failure during extended, long-duration tests at high temperature.

The current oxygen concentration in the Ya-21U NaK system was estimated before the start of thermal vacuum tests at the TSET facility and compared with specific system requirements (NaK oxide limit of 5-10 ppm). The evaluation performed and reported by Russian specialists determined that the current oxide concentration of the NaK coolant following final repair, refilling, cold trapping, and hermetic sealing was ~50 ppm. The Russian specialists also determined by calculation that the corrosive effects of the current oxide concentration on the austinetic stainless steels used for construction of the NaK system would not alter the serviceability of Ya-21U (Bogdanovich #19).

Nevertheless, tests of 1,000 hr in duration at temperatures above 450°C (723 K) were planned by TSET to demonstrate the integrity of the NaK system and components. The 1,000-hr tests were based on previous results obtained by Russian specialists, as previously described in Section 2 of this report.

3.3 MODAL TEST PREPARATIONS

The modal test was performed to obtain structural response data from Ya-21U for correlation of a finite element model which would be used during subsequent mechanical testing and structural evaluation of Ya-21U and EH-43 and EH-44 flight systems. Test preparations required installation of Ya-21U on a 21,700-lb seismic steel mass that was supported by air bags placed between the steel mass and high-bay floor of the TSET facility. An inspection platform was placed around Ya-21U to support low impact shakers, power and instrumentation cables, and test personnel.

Three low-impact shakers were installed to excite Ya-21U at selected locations. The shakers were supported by nylon straps secured to the inspection platform, as illustrated by Figure 31. Two of the shakers were configured to excite the bending modes and the other shaker was oriented to excite the torsion and axial modes. Figure 32 shows shaker orientations on Ya-21U. A separate modal test was performed on the radiator manifold which required a single shaker to be located between two legs of the Ya-21U truss support structure to excite torsion, axial, and ovaling modes.

Thirty-nine tri-axial accelerometers were bonded to various Ya-21U components and monitored during the tests. The axes were chosen to match the John Hopkins University, Applied Physics Laboratory's (JHU/APL) finite element model. The Y-direction matched Ya-21U's Y-axis; the Z-direction was Ya-21U's X-axis direction, i.e., vertically upward; and the X-direction was Ya-21U's Z-axis direction through one leg of the support structure.

Kistler tri-axes (100 mV/G) accelerometers were used at every point on Ya-21U; Endevco 7751 tri-axes (500 mV/G) were used on the seismic mass. Driving point accelerometers were mounted next to each PCB force gauge. All instrumentation was wired to the GenRad 2515 data acquisition system through a switch box. PCB amplifiers were used to amplify the signals and a

gain of 100 was used on the accelerometers. Sixteen channels of data were acquired at a time and a total of 123 channels of data were acquired, altogether. Each shaker had an independent flat random noise signal that was bandpass-filtered between 3 and 64 Hz (Mayes #20).

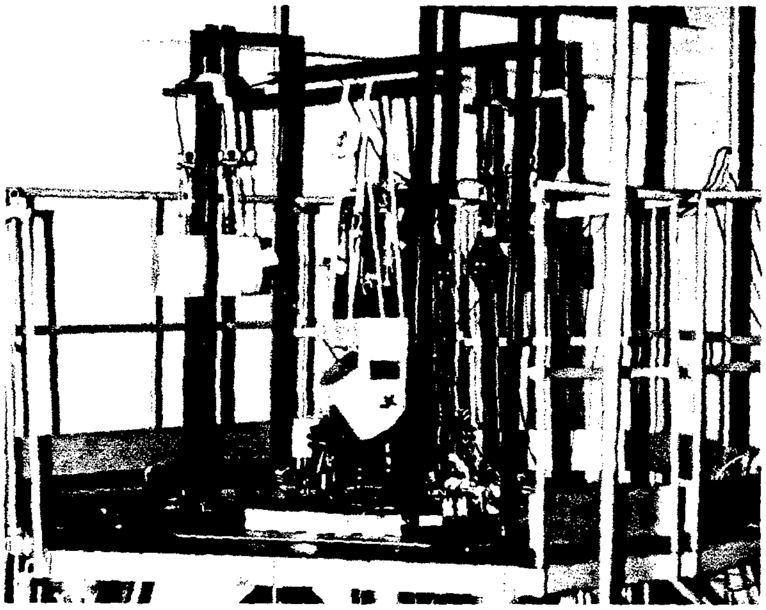


Figure 31. Shaker locations on the test fixture.

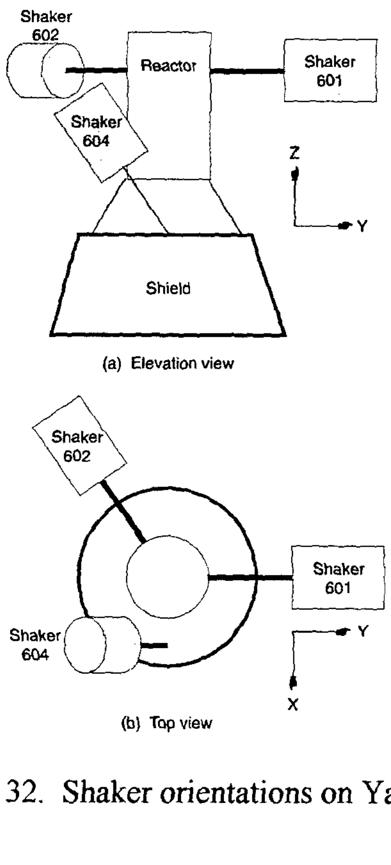


Figure 32. Shaker orientations on Ya-21U.

3.4 FIRST THERMAL VACUUM TEST PREPARATIONS

Preparations required to support thermal vacuum test #1 of Ya-21U included: functional and electrical tests; pre-tests and calibration of the Baikal test stand equipment; installation of Ya-21U; installation of heat sinks to cool the control rod drive motor, pressure sensors, and spacecraft interface connectors; installation and checkout of temperature sensors for special experiments; installation of a stainless steel thermal shield about the system radiator; installation of the cesium system evacuation line; preparation and installation of the TISA heaters; and performance of safety, test readiness, test procedure reviews.

3.4.1 Functional and Electrical Tests

The test procedure, methods, equipment, instruments, and special tools required and used during the functional and electrical testing were provided in detail by the translated Russian document, *1515-01-00010-PM-1*.

The reactor control mechanism, actuator drive motor, and automatic control circuitry were checked functionally with ground support equipment, a power supply, and a control panel, provided by Russian specialists with the TOPAZ II systems. The power supply permitted a smooth rotation of the nine control rods from zero +10/-2 degrees to the built-in rigid stop at 180 +15/-5 degrees. Panel lights on the control panel indicated actuation of the lower limit and middle limit switches in relation to the rotation of the No. 1 control rod position.

Results of the reactor control mechanism tests and free-play checks were in accordance with the requirements of Russian document, *182-01-0021 TU-1*. Free-play in the kinematic linkage of the control rod drive shaft for control rod No. 1 was less than 1 degree. In the range from 0 to 30 degrees, the free-play was less than 11 degrees. The arithmetic mean value of the free-play of all remaining shafts at each of the measurement points was less than 18 degrees.

The condition, status, and acceptability of the electrical system were determined by measurement and comparison of the electrical resistance of the circuits with previous results and standards, as listed in Table 16 for Ya-21U.

The insulation resistance between system circuits, emitters, bus-bars, the EM pump magnetic circuit, and circuits of electrical connectors to the Ya-21U frame were also checked and determined to be satisfactory.

The pressures in the Ya-21U gas systems and hermetically sealed control drive actuator were determined by comparison of pressure sensor data (potentiometer resistance) with previous recorded data and the pressure calibrations for each sensor.

3.4.2 Baikal Test Stand Pretest and Calibration

Before installation of Ya-21U in the vacuum chamber of the Baikal test stand, the facility power system, emergency power supplies, safety systems, test equipment systems and subsystems, and control room equipment and data acquisition systems were pre-tested, operated, calibrated, and accepted during previous tests performed on the V-71 system.

Table 16. Electrical resistance measurement of circuits of Ya-21U.

No	Circuit	Connector	Description	Method*
1.	Temperature sensors	9, 27, 31, 37	T1E, T2E, T3E, T4E, T5E, T6E, and T7E	6.5
2.	EM pump	31	Voltage terminals	6.11
3.	Cesium fuse retainer	20, 28	Cesium block valve	6.11, 6.12
4.	Step motor windings, M1 in drive AP	32	y1-01, 01-y2, y-02, 02-y4	6.11, 6.12
5.	Position transmitter, M2 of drive AP	32	Excitation & output windings	6.6
6.	Sensor R1 of drive AP	32		6.6
7.	Signal HKB1 of drive AP	32		6.6
8.	Signal KHB2 of drive AP	32		6.6
9.	Signal CKB of drive AP	32		6.6
10.	Unit T-46-2, Tn2	49		6.8
11.	Unit T-46-2, Tn2	49		6.8
12.	Motor for drives A3C1-A3C3	37		6.6
13.	Additional signal HKB of drives A3C1-A3C3	37		6.6, 6.9
14.	Signal BKB of drives A3C1-A3C3	37		6.6
15.	Signal HKB of drives A3C1-A3C3	37		6.6
16.	Mating control	9, 20, 27, 28, 31, 32, 37		6.7

* Document *1515-01-00010-PM-1*

The previous tests of the TOPAZ-II V-71 system demonstrated achievement of the following (Suriano #21):

1. TOPAZ-II power systems could be installed and connected to the Baikal test stand equipment.
2. Baikal test stand vacuum chamber, vacuum systems, cesium gas cavities, and cesium, evacuation system could be connected and hermetically sealed.
3. Data acquisition system and sensors could provide data within allowable errors.
4. Working section load could provide initial load of ~ 0.05 ohms.
5. Cesium evaluation line and interelectrode gaps of TFEs could be pressurized to ~4.5 torr with helium.
6. Cesium evaluation line could be hermetically connected to the cesium evacuation block.
7. Gas pressures of TOPAZ-II gas systems could be measured by system pressure sensors.
8. Reactor outlet NaK temperatures would not exceed 600°C (873 K) at TISA heater power levels below 105 kW.

9. Reactor outlet NaK temperature decrease during controlled cool-down would not exceed 100°C/hr.
10. The power of any single TISA heater would not differ more than 10 % from average of all other TISA heaters.
11. Resistance between TISA heaters and TFE cathode would not be less than 3 ohms.
12. TISA power increase increments would not exceed 5 A/min for TISA power below 5 kW and 10 A/min for TISA power above 5 kW. The first 5-step changes would not be greater than 15 W per TISA heater.
13. Load resistance changes would not exceed a 2-V step change within a 5-min period or exceed 0.5V/min smooth change.
14. Cesium pressure setting would not be less than 0.4 torr, and cesium pressure changes would not exceed 0.3 torr per step.
15. Working section current would not exceed 300 A.
16. EM pump voltage would not exceed 0.03 V per step.
17. Baikal test stand vacuum chamber pressure during system heat-up would be $\sim 4 \times 10^{-5}$ torr.
18. Cesium block pressure during heatup would be $\sim 1 \times 10^{-6}$ torr.
19. Cesium evacuation line could be maintained at temperatures above 290°C (563 K).

Some revisions and upgrades of control room equipment and data acquisition systems were required and completed to improve test operations and data handling for the Ya-21U test.

Before installation of Ya-21U, the checks listed in Table 17 were made of the Baikal test stand and the results recorded in the operations log book. Isolation resistance checks, listed in Table 18, were also made of the main power supply circuits.

3.4.3 Ya-21U Installation

Preparation of the Baikal test stand for installation of Ya-21U, indicated by Figure 30, included disconnection and roll-back of the two 10,000 l-torr/s turbomolecular vacuum pumps from the vacuum chamber and fore-vacuum lines; disconnection of water-cooling lines; and removal of the cover and mid-sections of the vacuum chamber from the chamber base.

Table 17. Baikal test stand checks prior to Ya-21U installation.

No	Check Made	Procedure	Logbook Format
1.0	Check of mech. equip inside of vacuum chamber	1515-97-0001 SB	1515-97-001 FO
2.0	Check of elect equip inside of vacuum chamber	1515-84-0002 PM	1515-84-0001 FO
3.0	Check of elect equip outside of vacuum chamber	1515-76-0001 PM	1515-76-0001 FO
3.1	Check of isolation resistance	1515-76-0001 PM, p. 4.1	1515-76-0001 FO Table 8.1, p. 1.3 Table 8.1, p. 3.4
3.2	Check of EWS system	1515-76-0001 PM, p. 4.2	
3.3	Check of TISA system	1515-76-0001 PM, p. 4.3	1515-76-0001 FO Table 8.1, p. 1.4
3.4	Check of EM Pump system	1515-76-0001 PM, p. 4.4	1515-76-0001 FO Table 8.1, p. 1.5
3.5	Check of MCRU system	182-178-0026 PM	182-178-0026 FO
3.6	Check of REH system	1515-76-0001 PM, p. 4.8	1515-76-0001 FO Table 8.1 p. 3.5
4.0	Check of mech. equip outside of vacuum chamber		1515-76-0001 FO Table 8.1
4.1	Check of evacuation system	1515-76-0001 TO, p. 7.1 1515-76-0001 PM p. 4.5	1515-76-0001 FO pp. 1.1; 1.2
4.2	Check of RVU and WMU EU	1515-76-0001 TO, p. 7.2 1515-76-0001 PM, p. 4.6	1515-76-0001 FO pp. 1.2; 2.3; 3.1; 4.1
4.3	Check of water supply system	1515-94-0072 MCh, p. 6TT	1515-76-0001 FO p. 2.1
4.4	Check of article charging system	1515-76-0001 PM, p. 4.7	1515-76-0001 FO pp. 3.2; 4.2
4.5	Check of gas supply system	1515-76-0001 PM, p. 4.7	1515-76-0001 FO pp. 3.3; 4.3

Table 18. Isolation resistance check of Baikal test stand main power supply circuits.

No	Procedure	Connector
1.	Disconnect 50/60 Hz transformer	
2.	Place all power tumblers on all instruments & panels in "OFF" pos.	
3.	Remove fuses from all instruments and units	
4.	Disconnect cables from Baikal connectors	1, 2, 8, & 48
5.	Measure isolation resistance between:	
5.1	TISA supply busses and chassis	
5.2	Supply/ output busses, TISA supply transformers, & chassis	
5.3	Primary and secondary coils of TISA dividing transformers	
5.4	Chassis and contacts of cable portion of connectors:	1, 8, 20, 34, & 48
6.	Replace fuses and connect connectors	

The inspection stand and plastic dust cover were removed from Ya-21U and the yoke lifting fixture installed. Following this, the system was lifted, separated from the inspection support legs, and installed in the Baikal test stand vacuum chamber, as indicated by Figure 33.

After the system was secured to the vacuum chamber, as indicated by Figure 34, work section power, control, and instrumentation cables were connected and checks made to assure proper isolation resistance. This was accomplished by disconnection of Baikal test stand connectors and circuit transformers and measurement of the isolation resistance (with a mega-ohmmeter set at 100 V) between the dividing transformer busses and transformer output busses and chassis.

3.4.4 Water Cooled Heat Sink Installations

Water-cooled heat sinks, required to simulate and maintain the thermal environment of space, were then secured to the radiator of the control rod drive actuator and to the pressure sensor group, as illustrated by Figure 35. Additional temperature sensors required by the experimental test plans are listed in Table 19. The sensors were secured to Ya-21U, as indicated by Figure 36.

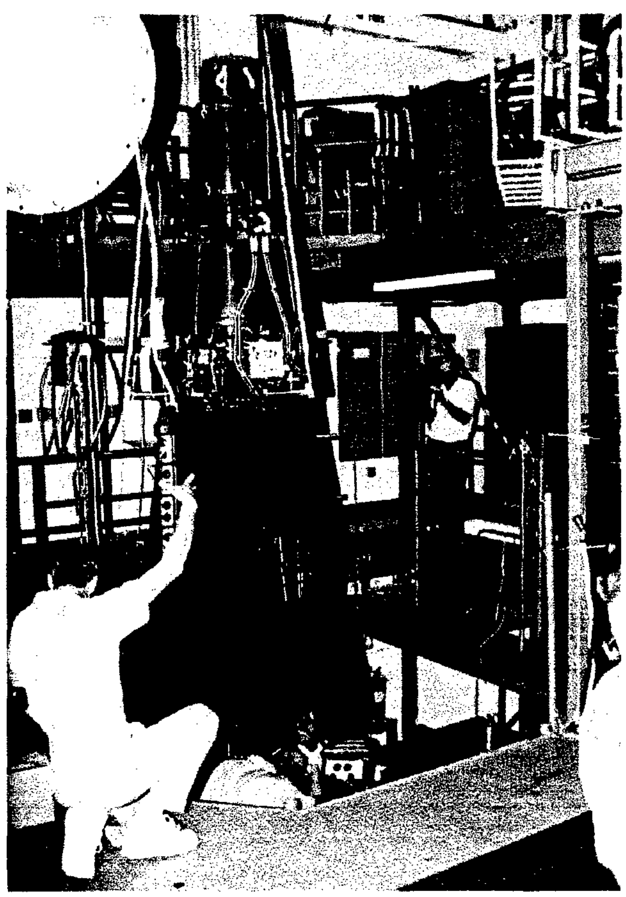


Figure 33. Installation of Ya-21U into Baikal test stand vacuum chamber.

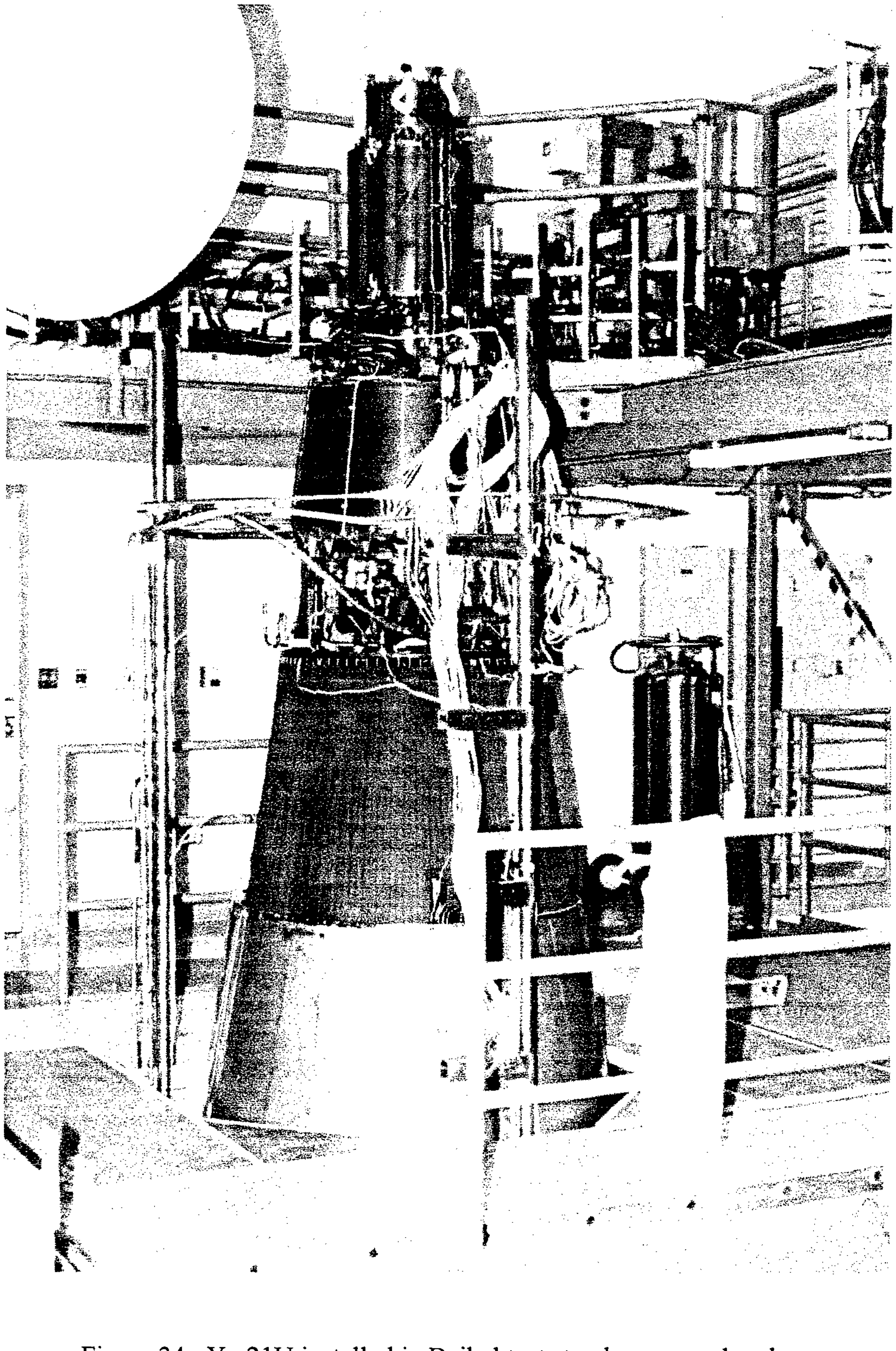


Figure 34. Ya-21U installed in Baikal test stand vacuum chamber.

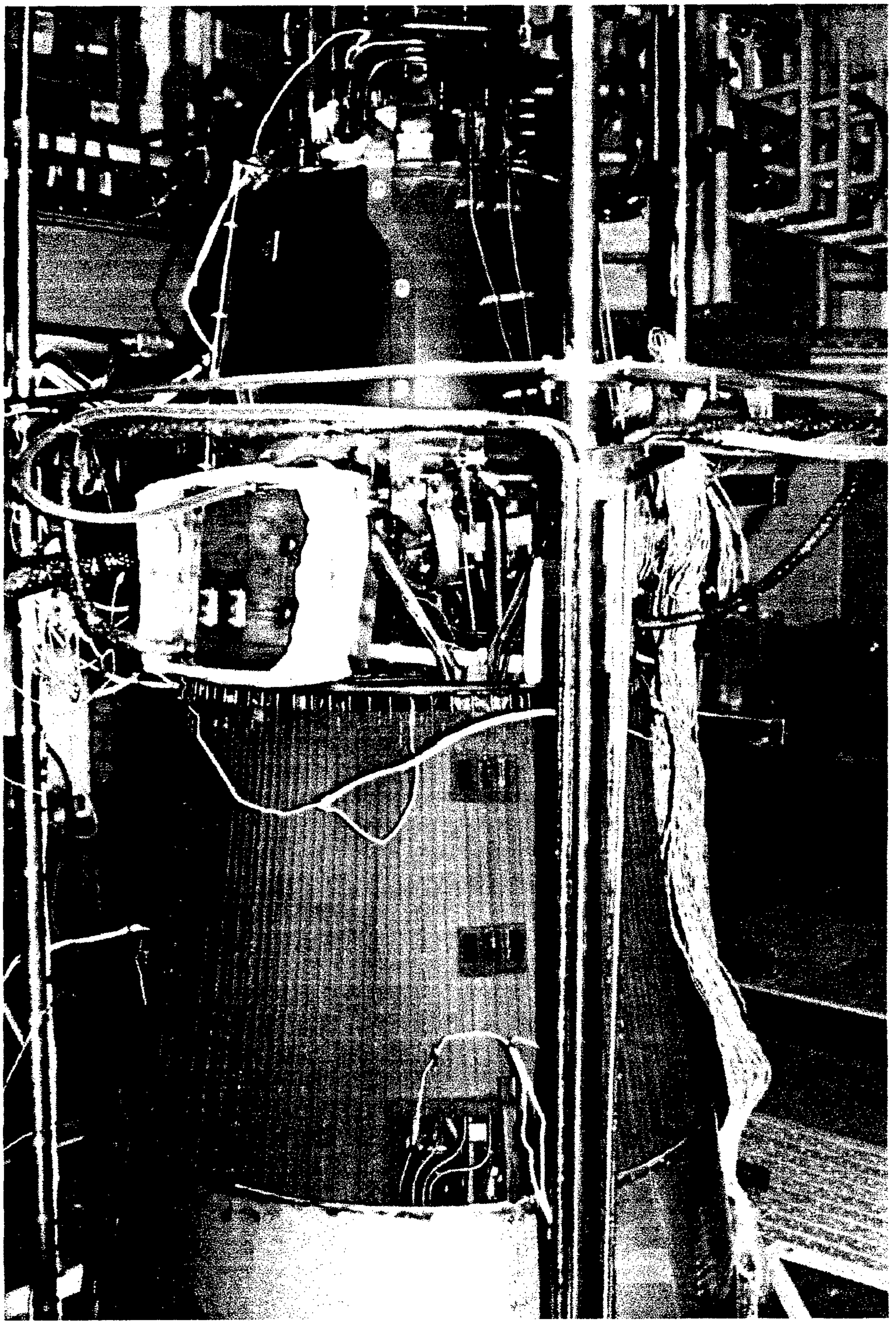


Figure 35. Heat-sink installations.

Table 19. Additional temperature sensors for experimental tests.

No.	Sensor	Sensor Location*	Parameter
1.	TM.1	Radiator-collector inlet (10:30)	Collector temp
2.	TM.2	Radiator-upper collector (2:30)	Collector temp
3.	TM.3	Radiator-upper collector (3:00)	Collector temp
4.	TM.4	Radiator-collector inlet (4:30)	Collector temp
5.	TM.5	Radiator-upper collector (7:30)	Collector temp
6.	TM.6	Radiator-upper collector (9:00)	Collector temp
7.	TM.7	Radiator-collector outlet (10:30)	Collector temp
8.	TM.8	Radiator-lower collector (2:30)	Collector temp
9.	TM.9	Radiator-lower collector (3:00)	Collector temp
10.	TM.10	Radiator-collector outlet (4:30)	Collector temp
11.	TM.11	Radiator-lower collector (7:30)	Collector temp
12.	TM.12	Radiator-lower collector (9:00)	Collector temp
13	TM.13	Radiator-tube (9:00)	Tube temp
14.	TM.14	Radiator-tube (9:00)	Tube temp
15.	TM.15	Radiator-tube (7:30)	Tube temp
16.	TM.16	Radiator-tube (7:30)	Tube temp
17.	TM.17	Radiator-tube (2:30)	Tube temp
18.	TM.18	Radiator-tube (2:30)	Tube temp
19.	TM.19	EM pump-NaK outlet tube	Outlet temp
20.	TM.20	EM pump-NaK outlet tube	Outlet temp
21.	TM.21	EM pump-NaK inlet tube	Inlet temp
22.	TM.22	EM pump-NaK inlet tube	Inlet temp
23.	TM.23	Cesium block-lower cover	Block cover temp
24.	TM.24	Cesium vapor line to plenum	vapor outlet temp
25.	TM.25	Cesium block NaK outlet pipe	NaK outlet temp
26.	TM.26	Cesium vapor line "U" section	"U" line temp
27.	TM.27	Cesium vapor "T" connection	"T" fitting temp
28.	TM.28	Cesium block valve cover plate	Cover plate temp

* North is 12:00

3.4.5 Temperature Sensor Installations

Prior to the 1000-hr thermal vacuum test, three U.S.-manufactured PT-103 RTDs were mounted on the lower radiator collector to compare their signal output characteristics with the Russian RTDs currently installed (Wyant #22). They were located close to the three Russian RTDs for direct comparison and correlation of their response during the startup, steady state, and shutdown phases of the system test. They were attached to the header pipe by a fiberglass wrapping that was secured in place with fiberglass string, as shown by Figure 36. The whole assembly was then covered with a stainless steel foil and secured by stainless steel safety wire. Four additional temperature sensors were secured to the EM pump inlet and outlet tubes, as shown by Figure 37.

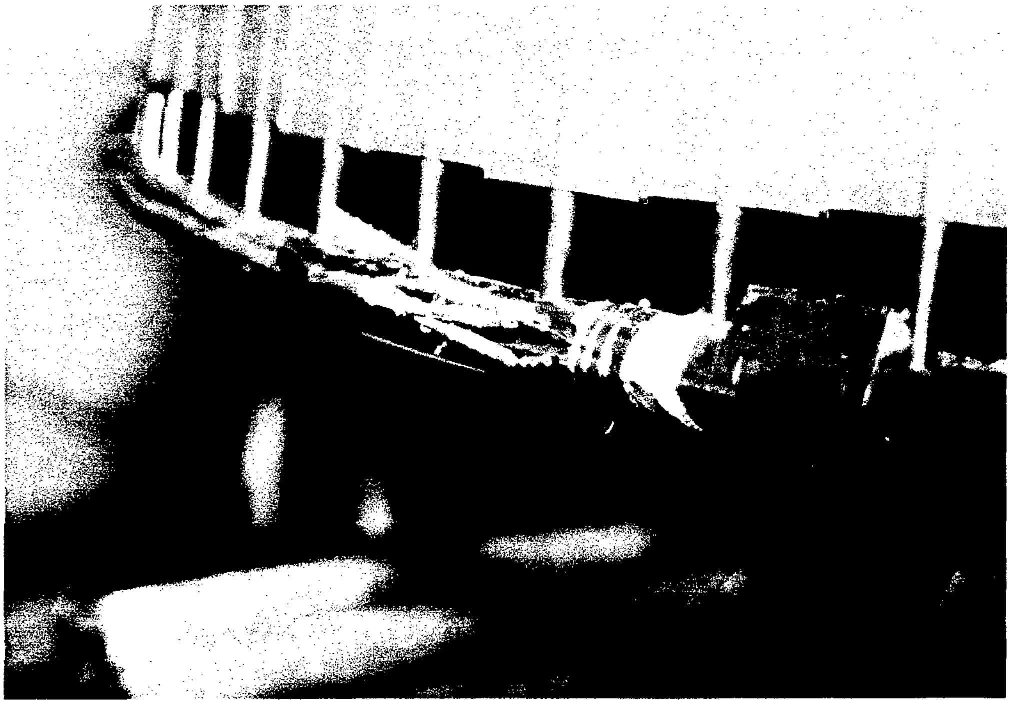


Figure 36. U.S. RTD mounting assembly on Ya-21U lower radiator collector.

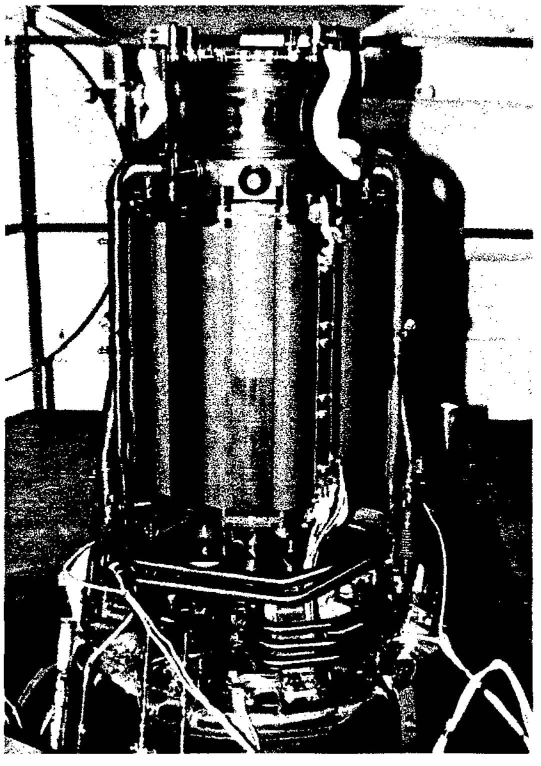


Figure 37. Temperature sensor installation on EM pump tubes.

U.S. RTD electrical leads were connected to lead wires inside the Baikal test stand vacuum chamber by spot welding to nickel collars on the signal wires. The lead wires inside the vacuum chamber were supported by the Ya-21U structure and connected to vacuum chamber hermetic seal feedthroughs. From the chamber feedthroughs, the signal lead wires were routed to the main terminal board located in the control room. Connection to the TSET DAS was made at the main terminal cabinet. The signal measurements and logging occurred automatically while the TSET DAS was operating. A 5-mA source current was applied to the circuit to measure the voltage drop and determine the RTD resistance. The allowed range for TSET DAS voltage measurements was 0 to +2 V. Russian RTDs were supplied with a 10-mA source current and monitored by the TSET DAS over the same voltage range.

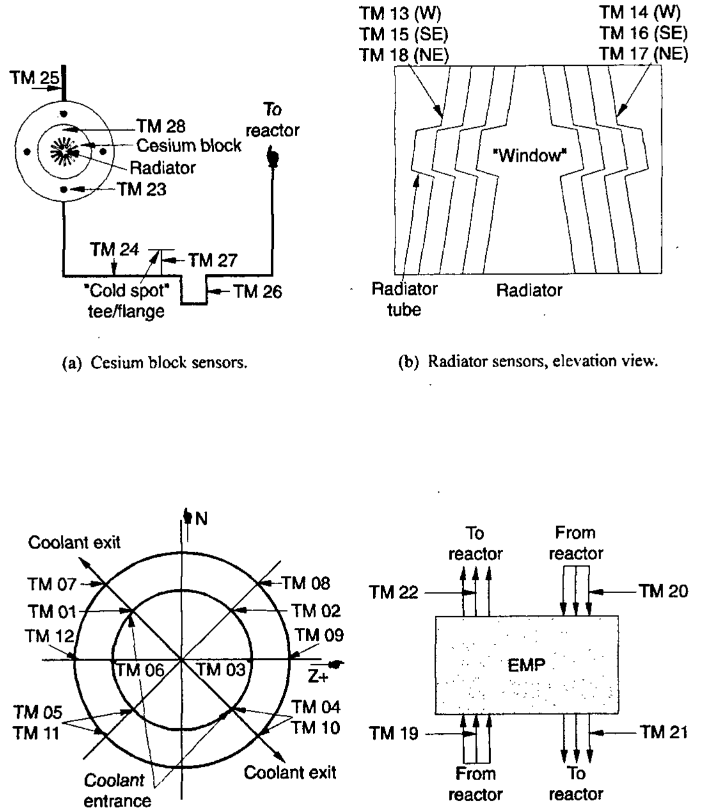
Thermocouple (TC) sensors were installed on Ya-21U and at selected positions on the cesium vapor supply line to the reactor cesium plenum. The censors on the system were required to permit thermal mapping and examination of the thermal characteristics of different Ya-21U subsystems and to enable modeling of the integrated system (Taylor #23). Temperatures along the cesium vapor supply line were required to explore possible output current oscillations of the thermionic converter work section that were observed during testing of the V-71 system.

Twenty-nine K-type TCs were placed at various positions on Ya-21U to monitor subsystem temperatures during the 1000-hr thermal vacuum test. Figure 38 indicates the locations of the TCs on the system.

Thermal mapping temperatures were monitored by the DAS and saved at a rate of approximately 1/min. The temperatures were monitored in real time so data problems could be noted and resolved. Data collection was done automatically every minute the DAS was operating. Approximately 18 megabytes of data were collected during the 1000-hr test (Taylor #24).

3.4.6 Thermal Shield Installation

A truncated conical shaped, stainless steel thermal shield, indicated by Figure 39, was designed, fabricated and installed around the lower half of the radiator. The thermal shield was installed to reduce heat rejected by the system radiator; to reduce thermal power of the TISA heaters required for operation at higher system temperatures; and to prevent overheating of the top end of the reactor assembly. (Previous Russian thermal vacuum system tests of Ya-21U at a TISA thermal power level of 123 kW caused overheating of the top end of the reactor assembly and TFEs, and may have weakened the upper brazed joints of the TFEs. This condition occurred because of heat losses from the TISA heater leads that extend down to the tungsten heating elements within the TFE cavities.) NOTE: This condition does not exist when the reactor core and TFEs are heated by nuclear fuel.



(a) Cesium block sensors.

(b) Radiator sensors, elevation view.

(c) Radiator sensors, top view.

(d) EM Pump sensors.

Figure 38. Thermocouple locations on Ya-21U used for thermal mapping.

Figure 39. Thermal shield installation around radiator.

3.4.7 Cesium System Evacuation Line Installation

Operation of the Ya-21U work section required the TFE interelectrode gap (space between the emitter and collector) to be filled with helium (at a pressure of ~7 torr) to improve heat transfer across the gap until the TFEs were ignited and operating. The addition of helium in the interelectrode gap also prevented voltage breakdown and arcing at low cesium pressures. After ignition, the helium gas was evacuated from the interelectrode gaps and replaced with cesium vapor at a predetermined pressure setting to improve the electrical output of the work section. The pressure and discharge rate of the cesium vapor were regulated automatically by the cesium block, which was heated by NaK coolant being returned to the reactor inlet.

To simulate system startup in space, an evacuation line was connected and hermetically sealed to Ya-21U's cesium discharge line and to the Baikal test stand cesium evacuation block. This evacuation line enabled evacuation of the helium and condensation of the cesium vapor that was discharged during system testing at operating temperatures. This line was heated throughout the system test to assure condensation of cesium vapor occurred in the condenser of the cesium test evacuation block, a subsystem of the Baikal test stand. During shutdown, the cesium line was dried by evacuation and condensation of the cesium and then backfilled with helium to the pre-startup pressure.

Attachment of the cesium evacuation line required removal of a short length (~40 mm) of tubing at each end of the Ya-21U cesium discharge/vent line and attachment of special "puncture valve" fittings, as indicated by Figure 40. This was done to permit several sequential connections to be made to the cesium discharge line without contamination of Ya-21U's cesium system and Baikal test stand cesium evacuation block. The special fittings were welded to the cesium discharge line using a tungsten inert gas (TIG) welder and an argon cover gas purge. The evacuation line was evacuated and welds leak checked with helium gas and a mass spectrometer leak detector. Following this, electrical heaters and temperature sensors were installed to control the temperature of the cesium evacuation line during outgassing prior to startup and cesium discharge during system operation.

3.4.8 TISA Heater Preparation and Installation

Thirty-seven tungsten electrical heaters (TISAs) were required for performance of non-nuclear thermal vacuum tests of Ya-21U. The TISA heaters supplied thermal power to the emitter sections of the 37 TFEs to simulate the heat provided by nuclear fuel. They were inserted into the emitter cavities, as indicated by Figures 41 and 42, which contain the UO_2 fuel pellets during nuclear system tests.

The TISA heaters for the Ya-21U thermal vacuum tests were used previously during the V-71 thermal vacuum system test. Prior to their initial use and insertion into the TFE cavities of the V-71 system, they were out-gassed to reduce potential contamination of the inner surfaces of the emitters during the initial heat-up of the V-71 system and to reduce the potential for arcing between the heaters and the TFE emitters. Out-gassing was performed on each TISA heater in a

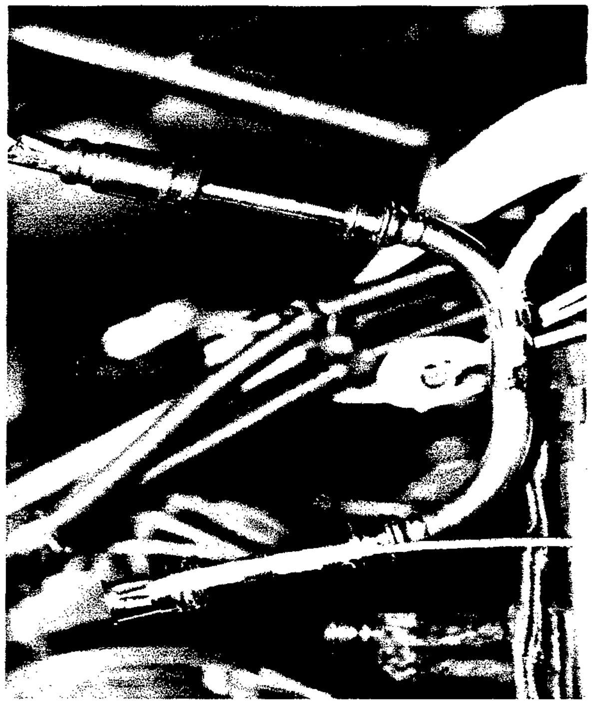


Figure 40. Cesium discharge line and puncture valve fittings.

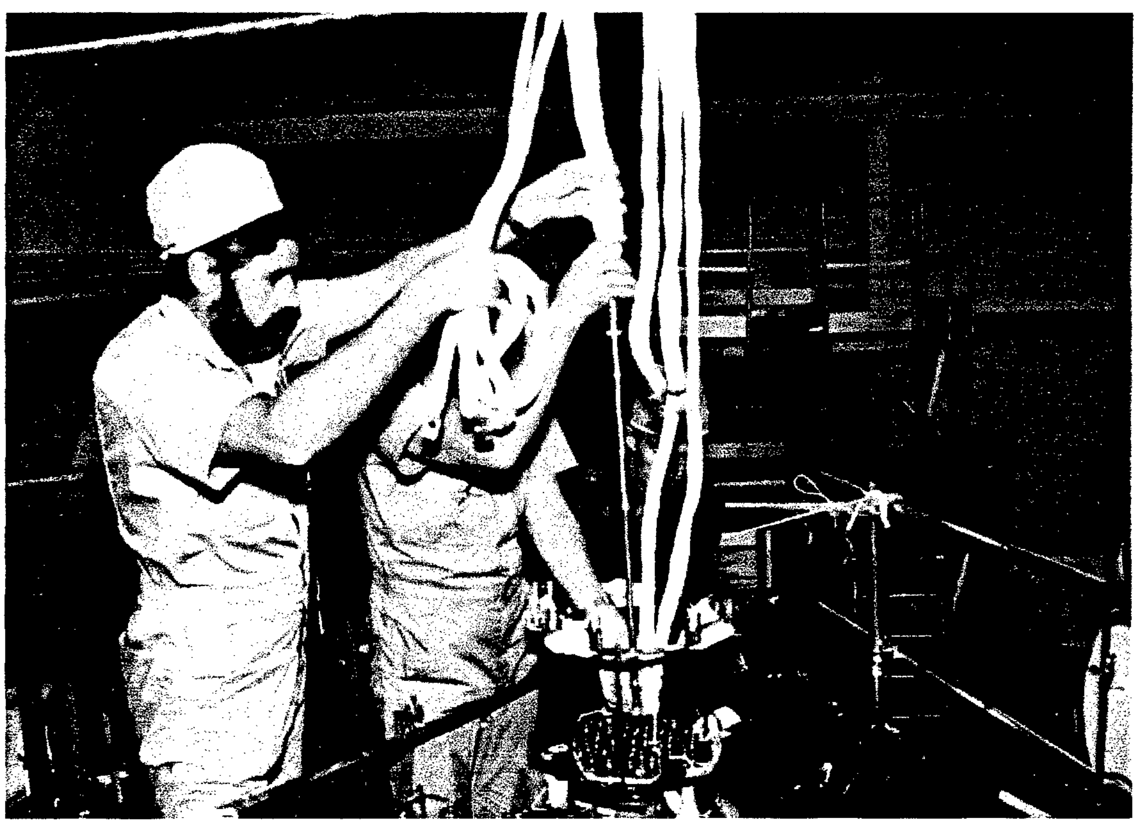


Figure 41. Electrical leads and TISA heaters.

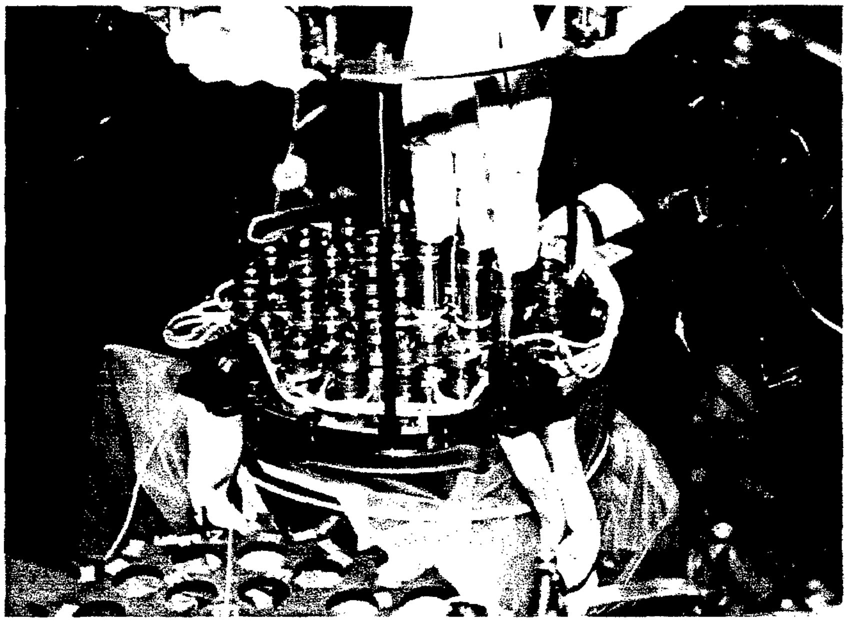


Figure 42. TISA heater installation in TFE cavities.

small vacuum chamber (TISA test stand) at a pressure of 5.0×10^{-6} torr at a heater power level of 100 W for a period of approximately 16 hr. This power level maintained the heater above tungsten re-crystallization temperatures and below that required to cause mass transport.

Resistance measurements were made during the out-gassing cycle to assure consistency within the set of 37 TISA heaters. Physical and electrical checks were made on each heater following removal from the out-gassing rig and before installation in the argon gas-filled storage container. At the conclusion of the V-71 system tests, the TISA heaters were removed, visually inspected, determined to be acceptable for continued use, and placed into argon gas-filled storage containers.

Prior to TISA heater installation in Ya-21U, each TFE emitter cavity was visually inspected, checked for dimensional variances using a go-no-go gauge, and cleaned with a lint-free tampon soaked with alcohol. The heaters were then installed and connected to the power cables, as indicated by Figure 43. Instrumentation cables were attached previously to each of the TFE voltage connections, as shown in Figure 44.

3.4.9 Safety and Test Readiness Reviews

Safety and test readiness reviews were conducted in accordance with the Ya-21U System Test Plan. Meetings, conducted with system test operation personnel, Russian specialists, and responsible members of program management, accomplished the following:

- Reviewed the purpose of each system test
- Assessed the status and actions to fulfill safety requirements

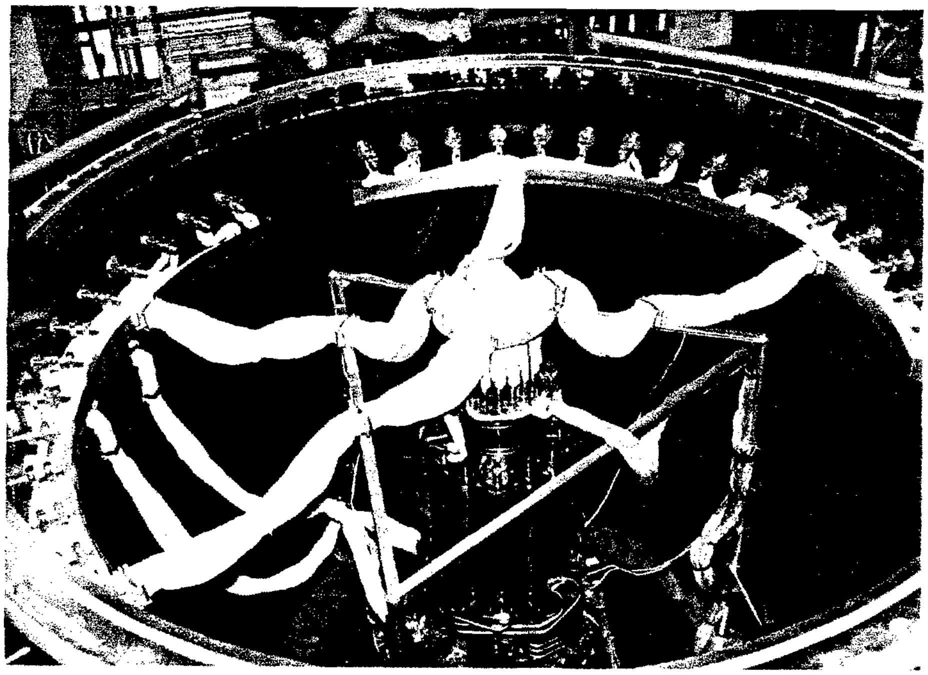


Figure 43. TISA heater power cable arrangement

Figure 44. TFE instrumentation cables.

- Assured completion of ambient functional tests, pre-test preparations, system modifications, sensor additions, Baikal test stand and test facility preparations; determined completion of personnel training and certification
- Confirmed Ya-21U test plans and procedures were complete, current, and available prior to the start of the first thermal vacuum test

A Safety and Readiness Review Report for the initial thermal vacuum system test was prepared and approved by Russian and U.S. specialists and the TSET Project Director.

3.4.10 Lessons Learned during Preparations for First Thermal Vacuum Test

Many learning opportunities occurred during delivery and inspection, pre-determination of the NaK system integrity, functional and electrical tests, Baikal test stand pre-testing and calibration, Ya-21U installation, thermal shield installation, cesium system evacuation line installation, and TISA heater installation. The lessons learned during these activities are described briefly below.

3.4.10.1 Delivery and Pre-Inspection

Ya-21U was delivered to the test facility in a Russian shipping container provided especially for TOPAZ-II systems. The container was sealed gas-tight and filled with a slightly positive pressure of argon (probably caused by temperature and altitude variations between St. Petersburg, Russia and Albuquerque, NM).

Before the seal was broken, several concerns arose and must be addressed during future TOPAZ-II system deliveries. They were:

1. Was an acceptable plan on-hand that identified the relevant issues, tasks, and responsible participants before the gas-tight seal was broken and the large hatch/door unbolted? (An approved plan was not available.)

2. Was the shipping container, including Ya-21U, subjected to severe shocks or vibrations during transportation from the time the system was installed in the shipping container to the time it was unloaded at the test facility? (Did not know, because shock monitors/recorders were not installed on the system or container prior to or during shipment.)

3. Was argon gas in the container and was the container free of toxic substances (NaK liquid, NaK oxides, and beryllium dust)? (The atmosphere inside the chamber was not sampled before the large hatch/door was opened.)

4. Were personnel, procedures, and equipment readily available to take appropriate action when the gas-tight seal was broken and the hatch opened? (Personnel were available; specific procedures and special equipment were not.)

5. Were other items, operations, and people at risk within the facility? (A Nak leak and potential fire would have required immediate action by trained personnel to confine the emergency. Beryllium reflector components were wrapped in plastic before shipment to confine beryllium particle dispersion during shipment.)

6. Were toxic measurements or samples taken as Ya-21U was removed from the container; were the samples analyzed, and how long did it take to get results? (Smear samples were taken to determine level of beryllium dispersion. However, results were not available for several weeks.)

7. Was Ya-21U moved to a secure and dust-free storage location? (It was secured.)

3.4.10.2 Document Inspections

The documents that relate specifically to Ya-21U were delivered at different times, by different means, and were received or provided by different Russian specialists. Also, the importance and priority for translation and distribution assigned to specific documents depended on immediate need, who needs them, difficulty to translate, and contractual obligations for payment. On many occasions, the very useful documents were hand-carried and kept by Russian specialists and did not become available until a problem was confronted or a specific question requiring the specific information was presented.

Document control, translation, assessment, reproduction and distribution, and revision became increasingly more complex and inefficient as the number of Russian sources, systems, contractual requirements for technology transfer, number of Russian specialists, and technical scope of the TSET Program increased. An extra-special effort was required to control original documents as they were received to prevent their loss and unavailability to support personnel. Non-translated Russian technical descriptions, specifications, procedures, and system and component test results have limited value and usefulness to the test efforts.

Periodic status reports of Russian documents received by control number, title, origin, document date, size/pages, priority, translator, translated date, and distribution status were essential to assure effective utilization of the high-cost translated documents.

3.4.10.3 Pathfinder System Modification

Ya-21U was configured for an inverted launch (reactor at the bottom) by Russian launch vehicles. This launch configuration altered the design of the startup unit, which included the startup battery, and its supporting structure; altered the design of the thermal cover and ejection mechanism; and changed the loads and stresses on the system's structure. This condition was pointed out by Russian specialists who recommended that modifications be made to the reactor support structure before mechanical system tests were performed.

As the Pathfinder System, Ya-21U represented the configuration that could be tested and launched. This required modifications to the existing system and required additional testing to confirm that the modifications were adequate. However, within the period between delivery of Ya-21U and preparations for thermal vacuum system testing, plans for flight demonstration of a TOPAZ-II system and spacecraft were deleted and only plans for ground non-nuclear tests remained. The unresolved questions became; what, why, and when should modifications be made to Ya-21U? This issue was finally resolved when it was decided to delay modifications until a specific mission application was established; to concentrate on the technology of the integrated system, and to explore the operating capabilities and limitations of single-cell thermionic systems. No missions were established and no modifications were made to Ya-21U by the TSET Program.

NOTE: The lessons learned by changing the TSET Program with flight demonstration as the primary technology transfer goal to a TSET Program with basic thermionic component and non-nuclear systems testing as the primary goal were significant; for example:

- Previous Russian space power technology transfer efforts were driven by a potential user's plans for its near-term application. When driven by a near-term application, technology transfer efforts must demonstrate that the space power system works as specified and predicted.

- With no immediate application, Russian space power technology transfer efforts were driven by an increased interest in how their system works and how this compared with current U.S. understanding of thermionic components and systems.

The variance in these two perspectives had a significant impact on TSET Program system test objectives, future plans, and costs.

3.4.10.4 NaK Coolant System Integrity

A common point of interest among proponents and adversaries of the TOPAZ-II space power system related to the number and causes of NaK system leaks during non-nuclear and nuclear system tests. This became a significant concern among Russian specialists prior to thermal vacuum system testing of the V-71 system in the Baikal test stand and continued to be a concern during testing of Ya-21U, as previously described in Section 2.

Two separate issues were related to the problem of NaK leaks in the primary coolant system and required resolution. The first issue was NaK coolant dissolves the stringers (impurities that were in the raw stock that were rolled out and exposed during the metal forming process) at operating temperatures and leaks result. The problem was caused by poor stainless steel material processes and quality control that produced an unacceptable raw product and subsequent finished parts that failed.

According to Russian specialists, the process was changed to require materials to be made by double-vacuum arc melting and clean cold working mills. However, systems V-71 and Ya-21U that leaked and were repaired, still contained radiator tubes, manifolds, and piping made from the old raw stock.

The second issue was repairs of the leaking systems, V-71 and Ya-21U, required removal and replacement of radiator tubes and sections of manifolds which exposed the remainder of the NaK coolant system to the atmosphere and potential contamination with small quantities of oxides.

The debates between Russian specialists related to the concentration of oxides in these two systems, V-71 and Ya-21U, and the potential for severe corrosion of their stainless steel system. The debate among Russian specialists focused on what corrective action should be taken to reduce the potential for failure. One group recommended draining, flushing, and refilling of the NaK coolant in each of the systems. This would have required a NaK loading system that was not available and a minimum of 6-8 months to construct, checkout, and refill the first system.

The other group wanted to sample the NaK coolant in the systems, have it analyzed for oxide concentrations, and then estimate the corrosion rate and lifetime of the systems based upon the oxide level in the samples. Cutting into the NaK systems to obtain a representative NaK sample would have increased the contamination of the systems and probably the sample, produced doubtful results, and possibly increased the potential for corrosion and failure.

The recommendation made by U.S. specialists was to estimate the oxide concentration resulting from previous repairs and system cleanup efforts and then to determine the potential for corrosion and failure thereafter. In other words, do not cut into the Ya-21U system -- leave it alone!

The evaluations made by Russian specialists on the Ya-21U system provided the following information(Bogdanovich #19):

1. During repair, the calculated content of oxygen entering the NaK loop from argon, used as a cover gas during repair, was ~2000 ppm.
2. Cold trapping of the NaK coolant following repair reduced the concentration of oxygen in the NaK loop to ~150 ppm (perhaps as low as 50 ppm).
3. The corrosion rate of the stainless steel in the NaK loop with an oxygen concentration 200 ppm would be ~13.2 mcm/yr. at a coolant flow rate of ~1 m/sec and at temperature of 500°C (773 K). The corrosion rate would be ~66.5 mcm/yr. at a temperature of 600°C (873 K).
4. The corrosion rates did not significantly alter the serviceability of Ya-21U during the planned duration of the demonstration tests.

Thousands of hours at operating temperatures were accumulated on Ya-21U since the decision was made to continue with the test plans, and no leaks were detected.

The lesson learned was simply this; Russian specialists' recommendations must be evaluated by U.S. specialists based on the technical and pragmatic issues involved from the perspective of U.S. specialists. In other words, do not fix something that seems to be working -- the solutions to perceived problems may become new problems that may be more difficult to solve, time consuming, and costly.

3.4.10.5 Functional and Electrical Tests

Functional and electrical test results of Ya-21U indicated negligible variance from previous test results performed by specialists in Russia. Performance of the tests provided an excellent opportunity for test operations personnel to participate in the testing activities and collection of data and was an efficient and cost-effective method for transfer of technology and training of operations personnel.

3.4.10.6 Baikal Test Stand Pretest and Calibration

Pre-testing and calibration of the Baikal test stand systems followed procedures similar to those that were used for pre-testing the V-71 system. Improvements made to the data acquisition system enhanced monitoring of system parameters and graphical display of test results. New active on-line graphical display of test results improved the performance of test operations and accelerated the technology transfer between operating personnel and Russian specialists. Variances and data anomalies were identified quickly and corrective measures implemented, when required(Wyant #22).

3.4.10.7 Ya-21U Test Thermocouple Installation

The planned experimental tests required additional temperature sensors to obtain information for thermal mapping and analysis of Ya-21U. Because of the concern for NaK leaks, direct attachment of additional thermocouples by spot welding on the Ya-21U NaK system was not permitted . Several other methods were considered to improve the thermal bond between the thermocouple sensor and the NaK system, to secure the sensor, and to insulate it electrically from the system. The method chosen was to secure all thermocouples with foil and stainless steel wire. Thermocouple wire leads were terminated inside of the vacuum chamber and connected to copper wires run to the data acquisition system.

Securing the thermocouples to the NaK system using foil and stainless steel wire did not assure a good thermal bond between the sensor and the surface of the NaK system piping and caused significant variances in the temperature data (Wyant #25).

3.4.10.8 Thermal Shield Installation

The requirement for a thermal shield around the Ya-21U radiator was not proposed by the Russian specialists until the decision was made to operate the NaK system at temperatures near 600°C (873 K) to demonstrate its integrity. At that time, it became apparent that many of the

system tests performed in Russia with TISA heaters were performed with a stainless steel thermal shield around the radiator.

Drawings were obtained that indicated the size and shape of the Russian thermal shield so a similar one could be fabricated for installation around the Ya-21U radiator. When the thermal shield was completed by a Russian technician, it became obvious that the shield was longer than the Russian thermal shield drawings indicated. The reason given by Russian specialists was that a longer shield was required to operate the Ya-21U NaK system at higher temperatures. When asked how long the thermal shield should be to permit operation of the NaK system at 600°C (873 K), the answer was the thermal shield should be the same length as the radiator. The consequence of the different sizes of thermal shields was that the thermal performance of Ya-21U in the Baikal test stand in the U.S. could not be compared directly with the thermal performance of Ya-21U in the same Baikal test stand in Russia.

Specific details of each system test, test arrangement, and test procedure must be discussed thoroughly with Russian specialists to assure complete understanding of Russian system test results and to enable comparison and correlation with system tests performed by U.S. operators.

3.5 TEST PREPARATIONS FOR THERMAL VACUUM TESTS #2 - #8

As indicated by Table 3 in Section 1, seven additional thermal vacuum system tests were performed after the initial 1000-hr performance test. These tests were performed to obtain information required to understand and explain previous test results; determine effects of the three emergency shutdowns caused by TSET facility equipment; observe system performance during expanded operating ranges of system loads, cesium pressures, and power levels; and compare operation and performance of the system with and without the thermal shield around the radiator.

3.5.1 Baikal Test Stand Preparations

On October 18, 1993, the cesium system and TFE interelectrode gaps were backfilled with helium to a pressure of 4.6 torr while the vacuum chamber was still under a vacuum. NOTE: At this time, the vacuum chamber was being prepared for disassembly to permit removal of Ya-21U for performance of the planned vibration and shock tests.

On October 19, 1993, the helium pressure of TFE interelectrode gaps was 4.4 torr. The small decrease in pressure from the previous day was attributed to the decrease in temperature of the converter work section and TFEs and ignored.. Thereafter, the vacuum chamber was backfilled with air to atmospheric pressure and disassembled to permit removal of TISA heaters from the TFE emitter cavities during the remainder of the day.

By the following morning of October 20, 1993, the gauge measuring the pressure of the TFE interelectrode gaps indicated more than 10 torr (high and off scale), a positive indication of a leak into the cesium plenum. Shortly thereafter, the cesium system was evacuated in steps to permit volume and pressure measurements. Based on these measurements, the initial pressure in

the cesium system was determined to be approximately 22 torr. Subsequent mass spectrometer analyses indicated elevated levels of nitrogen in the system and confirmed the presence of an atmospheric leak into the cesium system.

Various pre-determined valve manipulations and leak checks were performed and the leak was isolated to the upper end of the reactor assembly. A course of action was developed, the leak was confirmed, and isolated to the hermetic seals of TFEs #10 and #20.

The leak rate was determined using two independent procedures, one designed by Russian specialists and the other designed by U.S. operators. Both procedures determined the total leak rate for both TFEs to be approximately 3.5×10^{-3} l-torr/s. After determination of the leak rate, a joint decision was made by Russian and U.S. specialists to perform another thermal vacuum test to assess the minor effects on performance of the Ya-21U thermionic converter work section.

TISA heaters were re-installed, the vacuum chamber was re-assembled and evacuated, and preparations begun to repeat the Ya-21U thermal vacuum test. The previously planned vibration and shock tests were postponed until the effects of TFE leaks on performance of Ya-21U were determined and a performance baseline re-established to enable comparison of data before and after mechanical testing.

Ya-21U test #2 began on November 29, 1993 and was terminated abruptly on December 2 when the TISA heater input power was approximately 50 kW. This was the first emergency shutdown of Ya-21U at the TSET facility and was caused by a failure of the reduction gear in the motor generator of the uninterruptable power supply (UPS). The failure caused a complete loss of 50 Hz power to the TSET facility. Established procedures were followed for a complete loss of 50 Hz electrical power.

NOTE: When an unforeseen total loss of power occurs to TISA heaters during a system test, the EM pump is operated for an additional 30 s from an external battery to reduce system temperature transients. After the 30-s period, the system is cooled to ambient temperatures without pumped NaK coolant flow.

Although large thermal gradients occurred during the initial cooling and could have caused larger than normal thermal stresses, subsequent resistance checks of the TISA heaters and TFEs did not show any damage from the emergency shutdown. Repairs and re-tests of the UPS motor generator were performed and preparations for thermal vacuum test #3 of Ya-21U were completed prior to December 10, 1993.

Soon after the re-start of Ya-21U, the voltage symmetry of the converter work section shifted significantly and immediate action was taken by TSET operators to reduce the potential for arcing within TFEs that were operating at higher than normal voltages. The observed shift indicated a possible short to ground at TFE #26.

On December 16, the short to ground cleared by itself and the voltage symmetry returned to normal. This enabled completion of the test to evaluate the effects of the cesium leaks and the emergency shutdown.

3.5.2 Cesium Leak Assessments

Following shutdown and cool-down, leak rate measurements of TFEs #10 and #20 were performed. The leak rate had not changed significantly from that obtained before the UPS failure and previous emergency shutdown.

During the first three months of 1994, the Baikal test stand vacuum chamber remained open and permitted inspection of the TFEs in the area of the voltage symmetry shift. A small amount of corrosion was observed on the voltage pick-off device for TFE #26. After removal of the corrosion, resistance between the voltage connection and system ground returned to normal. Resistance to system ground tests of the other TFEs indicated normal values.

During this same period, the thermal shield surrounding the Ya-21U radiator was removed to evaluate system performance without the thermal shield and to compare the performance to that obtained previously by specialists in Russia.

3.5.3 Converter Voltage Symmetry Shift and Correction

On March 7, 1994, Ya-21U thermal vacuum test #4 was started. When the TFEs began producing power, a shift in the TFE output voltage symmetry re-occurred. The TFE work section appeared to be grounded again at TFE #26. Ya-21U was shut down and the vacuum chamber re-opened to permit another inspection of TFE #26. After removal of the TISA heater from TFE #26, a small metal flake was discovered in the narrow gap between the top of the TFE emitter and upper reactor vessel wall. A hypodermic needle, small enough to fit into the narrow gap, was chosen to extract the metal flake. During the attempt, the metal flake slipped further down into the inner, narrow gap and out of view. Because the lower section of the inner, narrow gap contains a TFE insulator, it was determined the small metal flake would not provide a circuit-to-system ground during further system test operations and was left in place. The consensus of opinions among U.S. and Russian specialists was that more unforeseen problems would have been created while trying to remove the metal flake from its new location.

3.5.4 Removal and Replacement of Thermal Shield

The Baikal test stand vacuum chamber was re-assembled and TISA heaters energized on March 12, 1994 to begin Ya-21U test #5. On March 13, 1994, at a TISA heater power of 82 kW, an automatic shutdown of the TISA heaters occurred due to a failure of a current meter used to monitor one of the three TISA heater subgroups. This was the second emergency shutdown of Ya-21U.

The current meter had failed in the high range and caused an automatic trip of breakers supplying power to the TISA heaters. Resistance measurements were performed on each of the 37 TISA heaters. Two TISA heaters had failed and required replacement.

After complete cool-down of Ya-21U, one team of operations personnel replaced the faulty current meter and performed calibration checks and inspections on all equipment used for monitoring of test systems and safety status. No additional problems were noted during these inspections. During this same period, another team of operations personnel opened the vacuum chamber and replaced the two failed TISA heaters for TFEs #2 and #26 and performed leak checks of all 37 TFEs. Leak rates of TFE #10 and #20 were determined and remained unchanged and no new leaks were discovered.

On April 11, 1994, Ya-21U test #6 began without the thermal shield. This time, Ya-21U was operated successfully for more than 250 hours at a TISA heater power level of approximately 85 kW. The system was cooled down to ambient temperatures to permit preparation for the planned vibration and shock tests.

However, post-test analysis of Ya-21U TFE performance data indicated an additional loss of work section output power had occurred since completion of the initial 1000-hr performance test. Preparations were made for testing of Ya-21U at system operating temperatures with the thermal shield re-installed around the lower section of the radiator. Two additional tests, #7 and #8, were performed during August 1994 to explore probable causes for the reduced output power of the TFE work section .

3.5.5 Lessons Learned during Preparations for Thermal Vacuum Tests #2-#8

The incursion of air into the TFE interelectrode gaps provided many opportunities to observe the effects of air and cesium system leaks on Ya-21U's performance. The lessons learned from these opportunities were:

- Helium leakage into the vacuum chamber from the interelectrode gaps of TFEs when the cesium system is backfilled with helium is the key indication of a leak in the cesium system, and should be monitored during evacuation of the vacuum chamber.

- After the first air incursion, operating procedures were not revised or updated for evacuation of the vacuum chamber with leaks in the TFE hermetic seals. This caused a second air incursion to occur in March of 1994. As a result, special procedures were developed for evacuation and back-filling of the vacuum chamber with the Ya-21U installed. In-depth training of all operations personnel was conducted.

- Procedures were developed and special test fixtures and equipment were fabricated to perform leak checks of individual TFEs. This procedure was implemented as part of the inspection and pre-test checks for all TOPAZ systems and the individual TFEs.

The reduction gear failure of the uninterruptible power supply system (UPS) was caused by improper maintenance by the service contractor (the reduction gear oil system was not filled properly). The facility maintenance procedures were updated to require that facility operators verify that an adequate amount of oil was added to the system by the contractor following maintenance. The design of the gear mounts was inadequate and caused excessive vibration of the power supply system. The gear mounts were stabilized.

The shift in voltage symmetry of the converter working section and subsequent discovery that a metal flake caused a shorting of a TFE required a special tool to remove the metal flake. The best tool for removing foreign material from the TFE and elimination of the short was a hypodermic needle attached to a vacuum cleaner.

After the failure of one TISA subgroup ammeter, it was discovered that the problem could have been determined during meter calibration. Operating procedures were revised to require that TISA current ammeters be calibrated prior to each startup of Ya-21U.

3.6 MECHANICAL TEST PREPARATIONS

Preparations for mechanical vibration and shock testing included: disconnection from the Baikal test stand, installation of accelerometers, installation of Ya-21U in the shipping container, and delivery to the mechanical test facility.

3.6.1 Post-Thermal Vacuum Inspections

Post thermal vacuum test inspections, functional tests, leak tests, and preservations procedures were performed prior to disconnection of Ya-21U from the Baikal test stand. Special procedures were also required and performed to reduce potential in-leakage of air into leaking TFEs during back-filling and removal of the vacuum chamber sections, disconnection of the TISA heater cables, and removal and storage of the TISA heaters.

Small cylindrical caps were fabricated and attached temporarily to the top of the reactor plenum to accommodate the small leaks observed in TFEs during the initial thermal vacuum tests. The caps permitted each leaking TFE to be protected from potential leakage of air into the interelectrode gaps and plenum during transportation and mechanical testing.

Functional and electrical tests were performed and results compared with data obtained prior to the first thermal vacuum tests.

3.6.2 Disconnection from Baikal Test Stand Interfaces

Disconnection from the Baikal test stand interfaces required removal of the thermal shield; disconnection of special temperature lead wires; disconnection, removal and storage of the TISA heaters; disconnection of water cooled heat sinks; preservations of the cesium system; de-

coupling of cesium evacuation piping; and disconnection of all power system electrical, instrumentation, control, and power cables.

Special procedures and fixtures provided with the Baikal test stand were used to pinch and seal the cesium evacuation line, prevent in-leakage of air, and to permit reconnection after completion of the mechanical tests.

3.6.3 Location and Installation of Accelerometer Sensors

Calibrated tri-axial accelerometers were secured to the designated Ya-21U components prior to placement of the system in the shipping container for delivery to the mechanical test facility.

3.6.4 Transportation to Mechanical Test Facility

Portable shock monitors were attached to Ya-21U and the shipping container to record shocks received during transportation and handling between TSET and SNL facilities.

3.6.5 Installation on Shaker Table

Upon arrival at the SNL test facility, Ya-21U was removed from the shipping container, rotated to the vertical position, and placed on the test fixture and secured. The test fixture was secured to a horizontal slip table to accommodate movement of Ya-21U during the 7-min sinusoidal and random vibration sweeps. The shaker head had been rotated previously on its mountings to provide the required horizontal, lateral Z-axis, input forces to the horizontal slip table.

3.6.6 Connection and Checkout of Accelerometers

The tri-axial accelerometers were connected to control and data acquisition systems and circuits checked for functional response.

Axial vibration and shock tests required Ya-21U and the fixture to be positioned vertically above the electrodynamic shaker head and supported by elastic slings. This arrangement unloaded the shaker head and permitted unrestrained movement of Ya-21U along its X-axis, vertical direction.

3.6.7 Safety Precautions

To ensure appropriate precautions were taken to prevent a release of hazardous materials from Ya-21U, an emergency response/site safety plan was developed for the mechanical test area. The plan was reviewed and approved by SNL's emergency management personnel.

The plan required that all emergency response equipment be on site during the entire test, and that the TOPAZ emergency response team be on site during testing. To reduce the spread of liquid metals, should a leak in the NaK coolant system develop, an eight foot high metal screen was fabricated and placed around the shake table. Carbon felt was also placed around the base

of the table to catch any NaK that would leak out during the test. The carbon felt would reduce the pyrophoric reaction that would occur when liquid NaK reacts with the atmosphere.

A beryllium survey was done prior to installing Ya-21U on the shaker table. Note: No beryllium dust was removed from Ya-21U and surrounding objects. All safety issues related to handling and testing of Ya-21U were identified, reviewed, and resolved by the TSET personnel before continuing with any portion of the system test procedures.

3.7 TEST PREPARATIONS FOR THERMAL VACUUM TESTS #9-#13

As shown in Table 3 of Section 1, five thermal vacuum system tests were performed after the mechanical test. The purpose of this series of thermal vacuum tests was to determine Ya-21U's performance following mechanical testing, to compare this performance with that obtain during thermal vacuum tests #7 and #8 in August 1994, and to conduct a simulated orbital (rapid) system startup.

To prepare for these tests, Ya-21U was removed from the SNL vibration test facility and transported back to the TSET facility at NMERI. The accelerometers used for mechanical testing were removed and a post-mechanical test inspection was made to determine if any mechanical change to Ya-21U had occurred. Thereafter, Ya-21U was installed in the Baikal test stand vacuum chamber and connected to the test stand interfaces. System leak checks were performed and leaks were discovered in the cesium exhaust line. This caused another air incursion into the interelectrode gap of the TFEs.

Additional leak checks were conducted to determine if changes in individual TFE leak-rates had occurred and to quantify the cesium exhaust line leaks. Final preparations were then made on the Baikal test stand and the vacuum chamber. The lessons learned during test preparations for thermal vacuum tests #9-#13 are included at the end of this section.

3.7.1 Removal and Transportation from the Mechanical Test Facility

TSET personnel moved the tri-legged handling fixture into place and attached it to Ya-21U using the overhead crane at the SNL vibration test facility. Mounting bolts were removed that attached Ya-21U to the vibration test fixture and then it was moved through the highbay corridor to an assembly area to install the strong-back sections and modified yoke handling fixtures. The strong-back, containing Ya-21U, was rotated to the horizontal position using the facility crane and wheels were installed to permit insertion of Ya-21U into the TOPAZ shipping container.

The shipping container was moved to a concrete apron just outside the test facility. The strong-back with Ya-21U inside was then installed and secured in the shipping container and the container sealed and backfilled with argon. A mobile crane placed the shipping container on a flatbed truck, secured it to the flatbed, returned it to the NMERI facility, and placed it in the TSET facility high bay with the facility's overhead crane.

3.7.2 Post-Mechanical Inspection of Ya-21U

After removal of Ya-21U from the shipping container and strong-back, the protective wrapping was removed from the reactor section, beryllium samples were taken, and the reactor section cleaned of trace amounts of beryllium.

Thereafter, all accelerometers were removed from Ya-21U in preparation for a detailed mechanical inspection. The accelerometers were removed from their mounting blocks and returned to SNL. Mounting blocks and dental cement used to attach the accelerometers to Ya-21U were removed using a heat gun to heat the cement until it became pliable enough to peel off. The cement residue on the surface of Ya-21U was removed by wiping with alcohol.

The mechanical inspection, defined by Russian procedure 1515-01PM[1], was completed during the period from September 12th to 16th, 1994. Discrepancies observed during this inspection were: a bolt on the semi-collar had come loose and fell off, a reactor lug fastening bolt had come loose, two coolant loop fastening bolts were slightly loosened, and fastening bolts on the rear of the startup unit mass-mockup had backed off by ~1.5 mm.

3.7.3. Installation and Connection to Baikal Test Stand Interfaces

From September 18th to 23rd, 1994, Ya-21U was placed in the Baikal test stand vacuum chamber and secured in preparation for testing. Interface connections were made between the reactor system and the vacuum chamber feed-throughs. U.S.-made thermocouples were attached to the radiator for thermal mapping. A new convection gas heat exchanger was installed inside the radiator and instrumented with external thermocouples to conduct the "flowing-gas heat exchanger" experiment (Wold #42).

During connection of the cesium evacuation line to Ya-21U, on September 23, 1994, a leak was discovered near a weld joint in the cesium reservoir exhaust outlet line. The interelectrode gaps of the TFEs were back-filled with helium to a pressure of 1.5 kgf/cm^2 to prevent continued air introduction into the TFEs. The CDBMB in St. Petersburg, Russia was notified immediately and was asked to provide recommendations for isolation of the leak. A plan was then developed to assess the location(s) of the leaks and to quantify the leak rates.

3.7.4 System Leak Checks and Assessment

Leak checks of TFEs #1, 7, 8, 10, and 20 were performed on October 6, 1994. Leaks had been detected in these TFEs prior to mechanical testing. The leak rate in TFEs #7, 10, and #20, had decreased approximately one decade. The leak rate in TFEs #1 and 8 were nearly the same. Specific leak rates obtained during the leak checks are listed in the Table 20 below:

Table 20. Leak rates of TFEs.

TFE No.	Leak-rate (mbar l/sec) taken on 8/22/94	Leak-rate (mbar l/sec) on 10/6/94
1	2.9×10^{-7}	3.9×10^{-7}
7	1.3×10^{-10}	< minimum detectable
8	4.6×10^{-8}	2.5×10^{-8}
10	2.3×10^{-6}	3.9×10^{-7}
20	6.9×10^{-7}	6.8×10^{-8}

On October 11, 1994, while performing a leak check of the cesium exhaust system, a leak in the piping from the cesium block was located in the area of a previous patch on the piping and in the area of a weld joint. The newly discovered leaks had leak-rates of 7×10^{-6} mbar l/sec and 4.5×10^{-5} mbar l/sec, respectively.

3.7.5 Baikal Stand Preparations for Thermal Vacuum Tests #9 - #13

The thermal shield was re-installed on the radiator of Ya-21U, and all instrumentation connections inside the vacuum chamber were made. Thereafter, TISA heaters were re-installed; vacuum chamber was re-assembled and evacuated; and preparations made to repeat the thermal vacuum tests of runs #7 and #8, which were performed prior to mechanical testing.

On October 20, 1994, the pre-startup checklist was completed, and system outgassing begun prior to the start of thermal vacuum test #9. System performance tests were then conducted and compared with previous thermal vacuum test results prior to the mechanical testing. A small decrease in the output power of Ya-21U was observed.

On November 13-14, 1994, Ya-21U was shutdown and cooled to <50°C. In the early hours of November 14, the first rapid startup of Ya-21U, thermal vacuum test #10, was conducted in the U.S. The rapid startup simulated a normal reactor startup in space. Ya-21U performed according to expectations - a valuable learning experience for all involved.

By November 17, 1994, several anomalies in system performance were noted. A group of individuals with varying backgrounds in thermionics gathered to analyze the unusual data that were being received. A short time later, a decision was made to shutdown Ya-21U and to determine the significance of the current data.

On December 6, 1994, thermal test #11 was started to investigate the previous operating characteristics displayed by Ya-21U. A second rapid startup was performed to determine if the previous rapid startup had affected system performance. Meetings were held daily to determine the appropriate action for forthcoming operations and were based upon analyses of data obtained during the previous day. On December 14, 1994, the system was shutdown once again to analyze gathered data and to place the TSET operations in standby for the holiday.

Thermal vacuum test #12 began on February 15, 1995, and was interrupted on February 17, 1995 for ~8 hr. by a failure of a current ammeter in a TISA subgroup that resulted in an emergency shutdown. A third rapid startup of Ya-21U was performed since the first two had shown step-reductions in output power of its thermionic converter work section. The third rapid startup and final thermal vacuum test #13 was begun on February 28, 1995 and continued uninterrupted to March 31, 1995.

A 200-hr hold at optimum output power was performed during thermal tests #12 and #13 to observe stable system performance. Based on Ya-21U system performance, it was postulated that the adjustable throttle valve used to set the cesium vapor pressure had malfunctioned, or that leak rates in individual TFEs had increased significantly and caused the cesium throttle valve to become ineffective. Since cesium supply pressure to the interelectrode gap was a critical parameter for testing the system, and there was no independent means of measuring cesium supply pressure on Ya-21U, several experiments were performed to verify the malfunction.

When "repeatability" could not be obtained with the cesium throttle valve at specific settings, it was closed. This permitted the cesium vapor supply pressure and thermionic converter output power to stabilize. The cesium pressure at the stabilized condition was estimated to be ~4 torr by comparison the current stabilized power output to a family of cesium pressure to power output characteristics obtained from previous tests. The remainder of thermal vacuum system test run #12 and run #13 were conducted with the cesium vapor throttle valve closed (at the maximum cesium pressure setting).

Near the end of the system testing, an increased reduction in Ya-21U system performance was observed and may have been caused by additional air incursion into the interelectrode gaps of the TFEs..

3.7.6 Lessons Learned During Preparations for Thermal Vacuum Tests #9 - #13

- The use of thermocouple wire, not previously out-gassed, for thermocouples attached to the radiator left a white residue on the radiator that was not easily removable.
- An independent means of measuring cesium system supply pressure is essential for future testing of thermionic systems.
- Thermal cycling and repeated rapid startups should be minimized during future testing of thermionic systems because of the excessive, non-prototypical thermal stresses applied to the system.

3.8 INSTALLATION OF NAK, CESIUM, AND GAS CHARGING SYSTEMS

Ya-21U was used as a template or fixture inside the Baikal vacuum chamber to position and install fittings, tubing, tube hangers required to connect NaK, cesium, and gas charging systems to the EH-44 system for anticipated pre-test preparations and performance of future acceptance tests. (Follis #26, Schreiber #27)

3.8.1 Installation of NaK Charging System

The NaK charging system design was based on the system used in Russia. Some modifications were made to incorporate additional safety margins and equipment available in the U.S. The NaK charging tank was originally the emergency NaK dump tank from the Russian Baikal test stand. The original NaK charging system design assumed that the NaK storage container would double as an emergency dump tank. For economic reasons, a U.S. Department of Transportation (DOT) approved NaK storage/transportation container was rented from Callery Chemical Co., for use as the NaK storage tank. One of the restrictions was that used NaK would not be drained into the tank. Because of this restriction, a stainless steel vessel was required and used as an emergency dump tank for the NaK system.

Several components from the original Baikal test stand were used during construction of the NaK charging system. They included a gas bubble check device, a level check tank, an argon receiver, a NaK pressure sensor, a eutectic drain valve and a eutectic fill/vent valve. The remaining components were provided by INERTEK.

To help minimize risks associated with a NaK leak at high temperatures, all NaK charging system piping and joints were wrapped with carbon felt prior to insulation of the piping. The carbon felt reacts slowly with exposed NaK in a controlled manner and minimizes the risk to operating personnel. Steel trays were also placed on the floor under the NaK system and steel side panels were mounted to deflect spray from a NaK leak to the steel pans. The tops of the panels were kept open to ensure adequate liberation of hydrogen that is released when exposed NaK reacts with the water vapor in the air.

3.8.2 Installation of Reactor Evacuation System

An additional 500 l/s turbomolecular pump, an ion pump, and various instrumentation were connected to the cesium evacuation system to be used during evacuation of the reactor plena. This system included a heated valve manifold specifically designed for evacuating and back-filling of TOPAZ-II systems.

3.8.3 Installation of Gas Charging Systems

Most of the gas system components were previous installed with the Baikal test stand. Minor modifications to piping, repairs to some of gas valves, and a gas mixing system were required.

3.8.4 Installation, Fit-up, and Checkout of Radiator Electric Heaters

The radiator electric heaters (REH) were shipped as individual component pieces from Russia. The components were assembled at the TSET facility and formed ten different sections and fitted around the Ya-21U radiator. The heater sections were cleaned and upgraded with new electrical insulators prior to their installation and thermal vacuum performance test, using Ya-21U as a substitute for the EH-44 system.

3.8.5 Lessons Learned during Preparation of Cesium and Gas Charging Systems

Russian made gas system valves had very fragile bellows that were damaged during initial assembly of the Baikal test stand. Failures of the gas valves were not detected until the gas system was checked out several years later. New gas valves were obtained and installed, which required removal of the Russian valves that were never used. An inspection and leak test of each Russian gas valve should have been performed prior to their installation.

3.9 PRESERVATION, REMOVAL, AND RETURN OF YA-21U SYSTEM

A contractual condition required Ya-21U to be returned to Russia after completion of the system evaluation tests. Pre-shipping preparations were performed to assure that Ya-21U would be preserved and returned safely and undamaged while in-transit aboard truck transports and cargo ships between Albuquerque, NM and St. Petersburg, Russia.

3.9.1 Preservation of Ya-21U System

The cesium supply system was backfilled with cesium to 1.05 kgf/cm^2 following completion of the REH performance test and prior to opening the vacuum chamber. After opening the vacuum chamber, the Ya-21U cesium system pressure was set slightly above atmospheric with helium. Thereafter, a standard vacuum-tight epoxy was used to seal the piping cracks of the cesium exhaust line. The procedure reduced the cesium system leak rate, but did not seal it completely. Helium pressure in the cesium supply system was maintained between 1.05 and 1.10 kgf/cm^2 for several days by the vacuum-tight epoxy..

TISA electric heaters were removed from the Ya-21U TFE cavities and installed in storage containers. Dust covers were installed over each TFE fuel cavity and secured.

A rubber gasket with holes for each TFE was fabricated, fitted, and cemented to the top of the reactor unit by Russian specialists. Helium pressure in the cesium supply system was raised to 1.1 kgf/cm^2 to back-fill the interelectrode gaps and then isolated. The remainder of the helium supply system was evacuated and back-filled with argon.

After purging the cesium exhaust line and TFE hermetic seals for several hours with argon, pre-fabricated caps were used to replace the dust caps on the top of leaking TFEs. A bolt-down device was used to seal the rubber gasket installed on the top of the reactor. The "K1" valve on the cesium block was then shut to isolate the cesium block/supply from the TFEs.

A clear plastic wrap was placed around the reactor section, checked for tightness, and secured in place. The wrap was used to contain any beryllium dust that may be generated during the transport of Ya-21U back to Russia.

Next, the cesium exhaust line was pinched and sealed by welding to isolate the cesium evacuation system. The thermal shield was removed, instrumentation wiring was removed, and all cables and connectors were secured to the frame of Ya-21U. Water-cooled heat sinks were removed from the automatic control drive and pressure gauge unit.

3.9.2 Removal and Preparations for Return of Ya-21U

Ya-21U was removed from the vacuum, placed in the strong-back assembly, and inserted in the TOPAZ shipping container. The container was sealed and purged with argon to 1.5 kgf/cm^2. Upon arrival of the truck, the shipping container with Ya-21U sealed inside was loaded on the flat-bed, secured, and transported to the seaport at Houston, Texas.

4.0 SYSTEM TEST OPERATIONS

4.1 INTRODUCTION

The first test of Ya-21U was a modal test of the system support structures to determine their response to low-level vibrations and shock forces and to provide low frequency structural response information for integration of the flight systems with launch vehicles.

The first thermal vacuum test began on August 30, 1993 with a slow heatup of Ya-21U to accommodate initial outgassing. Ya-21U operated normally for a period of 1,000 hr and confirmed the integrity of the NaK system since no NaK leaks occurred during this period of high temperature testing.

Ya-21U's performance compared favorably with previous Russian acceptance and high-power performance test results. Normal system cool-down was accomplished and preparations for disassembly of the Baikal test stand vacuum chamber were completed to permit removal of Ya-21U for the forthcoming shock and vibration tests.

On October 20, 1993, post-test inspections and pressure tests indicated leaks in the cesium system. The sources of the leaks were isolated to TFEs #10 and #20. Subsequent evaluations of the cesium system leaks were made and followed by a joint decision of U.S. and Russian specialists to re-test Ya-21U.

On November 29, 1993, Ya-21U heatup was begun and was terminated abruptly at a TISA heater power level of 50 kW. This was the first rapid cool-down of Ya-21U during U.S. testing. The shutdown was caused by a failure of the 60/50 Hz motor generator that provides electrical power to the Baikal test stand and TISA heaters.

On December 11, 1993, Ya-21U heatup was begun again. When the TFE work section started to produce electrical power, the voltage symmetry shifted significantly around TFE #26 for a period of time and then returned to normal. System performance and optimization tests were then repeated to determine effects of the first rapid cool-down and the leaks of TFE #10 and #20.

System test results obtained after 900 hours of operation during the first thermal vacuum test were compared with test results obtained after the discovery of the TFE leaks in December 1993. Following shutdown and cool-down, leak rate measurements of TFEs #10 and #20 were performed. The observed leak rate had not changed significantly from that obtained before the rapid cool-down.

The Baikal test stand vacuum chamber remained open during the first three months of 1994. This permitted inspection of the TFEs in the area of the voltage symmetry shift. A small amount of corrosion was observed on the voltage pick-off device for TFE 26. After removal of the corrosion, resistance between the voltage connection and system ground returned to normal. Low resistance to system ground data were not observed on any of the other TFEs.

On March 7, 1994, Ya-21U heatup was begun without the thermal shield. When the TFE work section started to produce electrical power, the voltage symmetry shifted significantly and was centered at TFE # 26. A normal cool-down was completed to permit detailed inspection of TFE #26.

On March 12, 1994, Ya-21U heatup was begun again and on March 13, 1994, another rapid cool-down occurred at a TISA heater power of 82 kW. This cool-down was caused by a failure of a Russian-made current meter used to monitor one of the three TISA heater power subgroups, which resulted in an automatic shutdown. This was Ya-21U's second rapid cool-down during U.S. testing.

On April 11, 1994, Ya-21U heatup was begun again without the thermal shield. This time, Ya-21U was operated successfully for more than 250 hr at a TISA heater power level of ~85 kW. After system cool-down, post-test analysis of the TFE performance data indicated an additional loss of work section output power had occurred since completion of the initial 1000-hr performance test.

Re-testing with the thermal shield re-installed on Ya-21U was started on August 1,1994 to explore probable causes for the reduced TFE work section output power and was completed on August 7. An additional test at system operating temperatures was started on August 11 and completed on August 17.

Vibration and shock testing of Ya-21U was performed in September 1994 at the SNL mechanical test facility. During the lateral sinusoidal and random vibration sweeps, force inputs and structural response were monitored and limited by accelerometers bonded to the fixture and to the upper plenum of the reactor assembly.

Axial vibration and shock tests were performed with Ya-21U supported by elastic slings and arranged vertically above the shaker head. As before, vibration sweeps, force inputs and structural response were monitored and limited by accelerometers bonded to the fixture and to the upper plenum of the reactor assembly. At the conclusion of the vibration sweeps of the X-axis, half-sine shock inputs to the X-axis were provided by the same electrodynamic shaker and test fixture.

Sensor data obtained during the mechanical tests were processed, printed, and provided by the SNL mechanical test facility to TSET for analysis and reporting.

After mechanical testing and inspection, Ya-21U was reinstalled in the Baikal test stand, checked out, and restarted slowly to out-gas new TISA heaters and Ya-21U. During the first heatup, the cesium throttle valve became difficult to turn, was cycled frequently, and then adjusted to permit comparison with previous performance test results. This event focused the attention of U.S. and Russian specialists on the effects of oxygen intrusion into the cesium system and thermionic converter work section of Ya-21U. Subsequent thermal vacuum tests provided many opportunities to explore these effects on Ya-21U performance.

4.2 MODAL TEST OPERATION

To obtain modal test information, Ya-21U was secured to a heavy seismic steel mass that was installed temporarily on the highbay floor of the TSET laboratory. Three low-impact shakers were used to excite Ya-21U at selected locations. Shaker input forces were less than 10 lb. and the bandwidth was 3-64 Hz. Burst random inputs were used to excite the structure for 2 seconds during the 8-second sample period. A separate modal test was also performed on the radiator manifold. Tri-axial accelerometers were bonded to various Ya-21U components and monitored during the tests. The axes were chosen to match the John Hopkins University, Applied Physics Laboratory's (JHU/APL) finite element model. All instrumentation sensors were connected to a data acquisition system and amplifiers were used to amplify the signals from the accelerometers. Sixteen channels of data were acquired at a time. Altogether, a total of 123 channels of data were acquired. NOTE: Details of modal tests and results are presented in Section 5.

4.3 FIRST THERMAL VACUUM TEST OPERATION

4.3.1 Pre-startup Thermal Vacuum Checks

Initial evacuation of the chamber was begun on August 2, 1993, after installation of Ya-21U and connection of the cesium vapor discharge line. During the evacuation, helium leak checks were performed to verify the integrity and leak tightness of the vacuum test chamber and internal cooling water piping. Also, the cesium vapor discharge line, located outside the vacuum chamber, was out-gassed at operating temperatures using electric heaters. The entire line was leak-checked with helium.

After satisfactory completion of the leak checks, the vacuum chamber was opened to complete connection of electrical, cooling, and data acquisition equipment. During this time, the stainless steel thermal shield was installed around the lower section of the radiator; the Baikal test stand vacuum chamber was re-assembled; and the data acquisition system was checked for operability. Upon completion of vacuum chamber evacuation, additional outgassing and helium leak checks were performed on the cesium vapor discharge line and vacuum chamber.

Preparations were made to operate the evacuation puncture valve of the Ya-21U cesium block. The puncture valve consisted of a "fusible" stainless steel pin, which was melted by an electric current that passed through the pin. When the fusible pin melted, a spring forced a hollow needle-point device to puncture a stainless steel membrane seal and opened a path from the inner electrode gaps of TFEs to the cesium vapor discharge line. Verification of the puncture valve operation was determined by resistance measurements of contacts associated with the valve. After the puncture valve was opened, a near zero resistance was expected.

On August 29, 1993, an electrical current was passed through the fusible pin to open the puncture valve. The measured resistance of the open indication contact terminal was higher than expected and caused some doubt about penetration of the membrane by the puncture device.

In addition, a higher than expected pressure rise occurred in the cesium evacuation system, which prompted immediate attention. For example, if the puncture valve was opened, then the unexpected pressure rise in the cesium evacuation system would have been caused by an air leak into the TFE interelectrode gaps with unpredictable consequences.

An immediate course of action verified that the valve was open. As part of this procedure, checks were conducted to determine whether either air leaked into the TFEs or the pressure gauge was stuck during the pressure transient. (NOTE: The gauge had a maximum differential pressure range of 10 torr and had stuck on two previous occasions.) A valve was opened to evacuate one side of the differential pressure gauge and as soon as this was done, the gauge responded and stabilized at 0.8 torr pressure in the cesium discharge system. Using this value, the initial pressure was calculated to be 3.6 torr for the TFE gaps, which agreed with the previous pressure of approximately 3.4 torr of helium recorded by Russian specialists.

Another check was performed on the cesium vapor discharge system to determine its volume. This check used the pressure change between different portions of the system that could be isolated by valves. It was determined that the puncture valve was opened and operations could continue. Mass spectrometer data on the gas in the TFEs confirmed that air had not leaked into the interelectrode gaps. The TFE gaps were backfilled to a pressure of 0.6 torr with helium to assist heat transfer and to minimize potential arcing within the TFEs during heatup of Ya-21U.

4.3.2 Startup of Ya-21U

After completion of pre-startup checks, an operations safety, readiness, and test review was conducted. Operation personnel, Russian specialists, and members of management reviewed test plans, determined status of safety requirements, and assured pre-test facility preparations, personnel training, and certification. Test procedures were completed, current, and available prior to start of the first thermal vacuum test on Ya-21U by U.S. operators.

On August 30, 1993, the NaK system EM pump and TISA heaters were energized and a slow heatup of Ya-21U was begun. The normal startup sequence consisted of a slow heatup of the system with the Baikal test stand vacuum chamber pressure below 10^{-5} torr. The TISA heaters had an upper operational pressure limit of 5×10^{-5} torr to permit outgassing and prevent damage to the TISA heaters. The initial heatup rate of Ya-21U was limited by the outgassing of system components and devices inside the vacuum chamber.

The EM pump was initially operated with an external supply of current of approximately 350 A. At a total TISA heater input power of 40 to 45 kW, the externally supplied EM pump voltage was increased to 0.32 VDC, which provided a DC current of approximately 800 to 900 A. The increase in current to the EM pump changed the NaK system temperatures.

When the NaK outlet temperature exceeded 350°C (623 K), the cesium block throttle valve was adjusted to provide a cesium vapor pressure of 0.6 torr in the TFE interelectrode gaps at normal system operating temperatures. When TISA heater power reached ~70 to 80 kW, the TFE work section began to produce electrical power. During system operation, the three parallel-

connected pump section TFEs began supplying current to the EM pump through Ya-21U onboard connections, and EM pump voltage was maintained at 0.32 VDC with a corresponding reduction in externally supplied current. During operation, current and voltage levels were indicated on the computer data acquisition system (DAS) for the 34 series-connected TFEs in the working section that supply power to the Baikal test stand load.

When the working section output current was greater than 30 A, the helium pressure in the TFE interelectrode gap was reduced in 1-torr increments. At the end of each step of helium pressure reduction, increases in output power were verified before commencing the next step. The increase in output power indicated the TFEs were operating normally, and cesium vapor was being provided by the cesium block to the TFE interelectrode gaps. When the cesium pressure in the TFE interelectrode gaps reached 0.6 torr, TISA heater input power was increased to a nominal 85 kW.

During this period, voltage symmetry of the TFE working section was checked to ensure there were no shorts or grounds within the working section. Additionally, the electrical resistance between each TISA heater and its respective TFE cavity was measured to determine the extent of bowing or deformation of the TISA heater tungsten filaments. Upon satisfactory completion of resistance and symmetry checks, the output power load was adjusted to increase output voltage within the range of 20 to 30 VDC, as required to perform planned system tests. NOTE: Details of experiments during this period and results are presented in Section 5.

4.3.3 Ya-21U System Shutdown, Leak Detection, and Voltage Symmetry Shift

The operation of the Ya-21U continued for a period of ~1,000 hours at a NaK outlet temperature >450°C (723 K). After this period, Ya-21U was shutdown and cooled to ambient temperature between October 15-17, 1993. The normal system shutdown required a gradual decrease of TISA heater input power and operation of the EM pump with externally supplied current. The cool-down rate was limited by procedure to 100°C/hr (100 K/hr) and was normally controlled at ~50°C/hr (50 K/hr) to minimize thermal stresses on components.

On October 18, 1993, the cesium system and TFE interelectrode gaps were backfilled with helium to a pressure of 4.6 torr while the vacuum chamber was being prepared for disassembly to permit removal of Ya-21U for performance of planned vibration and shock tests.

On October 20, 1993, the pressure of the TFE interelectrode gaps was more than 10 torr (high and off scale), a positive indication of leaks from the hermetic seals of TFEs #10 and #20, as indicated by Figure 45. An analysis of data from the 1,000-hr test indicated the leaks may have developed some time between 200 and 700 hr of system operation. Details of the analysis of the effects of the leak are discussed in Section 6 of this report.

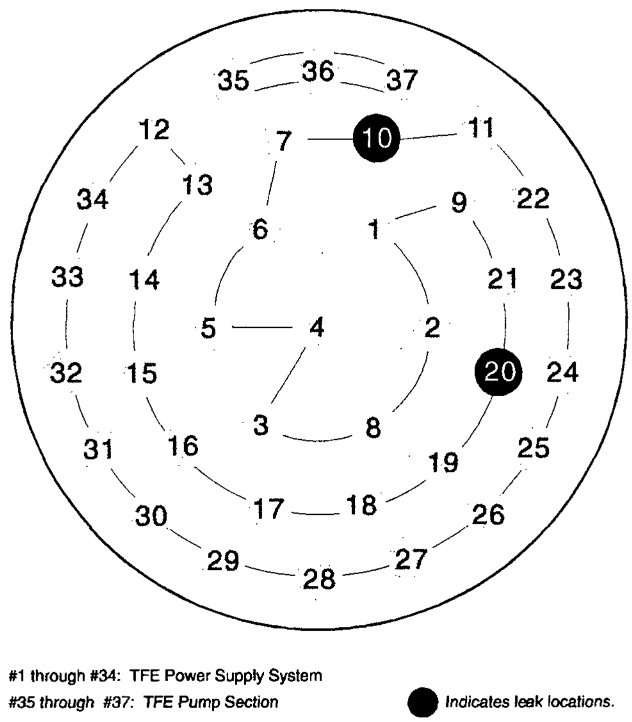


Figure 45. Top view of TOPAZ II reactor showing leak locations for Ya-21U.

Ya-21U system test operations resumed on November 29, 1993. On December 2, the Ya-21U system TISA heater input power was approximately 50 kW when the UPS failed and caused a complete loss of 50 Hz power to the TSET facility. Established procedures were followed for a complete loss of 50 Hz electrical power. Subsequent resistance checks of the TISA heaters and TFEs did not show any damage from the rapid cool-down.

The thermal vacuum system test was restarted on December 10. On December 12, 1993, the TISA heater power and system temperatures were sufficient for the TFEs to start producing output power. At this time, the voltage symmetry of the TFE work section shifted ~ 66 %. The load resistance and output voltage were lowered immediately to reduce the potential for arcing within TFEs that were operating at higher than normal voltages caused by the symmetry shift. Subsequently, NaK flow-rate, TISA heater input power, work section output voltage, and current were varied to determine the effects on voltage symmetry of the TFE work section. No noticeable effects were observed.

Minor mechanical agitation of the Baikal test stand vacuum chamber that contained Ya-21U caused slight shifts in voltage symmetry of the TFE work section. These observations led operations personnel to believe the shift in voltage symmetry was caused by an electrical ground within the TFE work section. On December 16, 1993, the voltage symmetry shift cleared itself unexpectedly and returned to normal. Power optimization tests were performed to compare test results with the previous 1,000-hr test results to determine the effects of TFE leaks on Ya-21U output parameters.

System test results obtained after the discovery of the TFE leaks in December 1993 were compared with system test results obtained after 900 hours of operation during the first thermal vacuum test, as listed in Table 21.

On March 7, 1994, Ya-21U was re-started. When the TFEs began producing power, a shift in the TFE output voltage symmetry re-occurred. The TFE work section appeared to be grounded again at TFE #26. Ya-21U was shut down and vacuum chamber re-opened to permit another inspection of TFE #26.

4.3.4 Ya-21U Operation Without Thermal Shield

The Baikal test stand vacuum chamber was re-assembled and TISA heaters energized on March 12, 1994. On March 13, 1994, at a TISA heater power of 82 kW, an automatic shutdown of the TISA heaters occurred due to a failure of a current meter used to monitor one of the three TISA heater subgroups. The current meter failed in the high range and caused an automatic trip of breakers supplying power to the TISA heaters. After completion of procedures for an automatic shutdown of the Baikal test stand systems, resistance measurements were performed on each of the 37 TISA heaters. High circuit resistance (open circuits) were observed on two TISA heaters, located in TFEs #2 and #26, and required replacement.

Table 21. Ya-21U output power optimization data before and after TFE leak detection.*

10/14/93					12/18/93			
V_{WS} VDC	I_{WS} A	P_{WS} kW	$T_{NaK\ out}$ °C		V_{WS} VDC	I_{WS} A	P_{WS} kW	$T_{NaK\ out}$ °C
20	107	2.14	534		20	115	2.30	532
22	105	2.31	534		22	107	2.33	532
24	98	2.36	533		24	98	2.36	532
26	91	2.36	533		26	91	2.37	52
28	85	2.39	533		28	86	2.39	532
30	80	2.40	533		30	80	2.39	532

* Electrical power output parameters at 90 kW TISA power and 0.6 torr Cs pressure.

On April 11, 1994, Ya-21U was re-started and a slow heatup to normal operating power of 85 kW was completed on April 15, 1994. Ya-21U was operated for more than 250 hr to conduct planned experiments, obtain power optimization data, and evaluate performance. A comparison of optimization data without the thermal shield with data from previous Russian tests was made and is provided in Table 22. Note: Results of system experiments were included in Section 6.

4.3.5 Ya-21U Operation With Thermal Shield

Evaluation tests of Ya-21U with the thermal shield were performed again during the fall 1994. The tests included repetition of previous system tests to obtain optimization data with the thermal shield. In addition, thermal and hydraulic tests were performed to obtain data for other subsystems and components that may be installed on TOPAZ II systems in the future.

Table 22. Comparison of Ya-21U power optimization data.

Parameter	Units	Russian Test April 1990	U.S. Test April 1994
TISA Power	kW	85.6	85.0
Cesium Vapor Pressure	torr	0.6	0.6
Work Section Current	A	80	71
Work Section Voltage	VDC	27	28.1
Work Section Power	kWe	2.16	2.00

4.4 MECHANICAL TEST OPERATIONS

Mechanical tests of Ya-21U were performed at SNL's mechanical test facility. An electrodynamic shaker was used to provide both vibration and shock forces to the structural interface connections located at the lower end of the system. Vibration and shock tests and were performed at reduced stress levels below anticipated launch levels. Test procedures, test levels, and test duration were established and approved through joint efforts of JHU/APL, U.S. Phillips Lab, Russian personnel, and SNL mechanical test personnel. The test levels were based upon selected loads and the test environment, as listed in Table 23.

Table 23. Planned simulated launch loads for Ya-21 acceptance tests

Vibration:	
Sine Vibration	Level: g (1 min @ axis)
Frequency - Hz	
5	.25
5 - 8	----- (linear increase)
8 - 40	1.0
40 - 100	.9
100 - 200	.8
Random Vibration	Level: g^2/ Hz (1 min @ axis)
Frequency - Hz	
20 - 70	.02
70 - 100	----- (linear increase)
100 - 800	.06
800 - 2000	----- (linear decrease)
2000	.013
Shock:	
Axial - Frequency - Hz	Level: g
10	2
10 -100	----- (linear increase)
100 - 500	40

Note: Notching of input values was employed when resonance occurred to avoid dangerously high response.

4.4.1 Functional Testing of Test Equipment, Sensors, and Data Acquisition System

Ya-21U was secured to the test fixture, as illustrated by Figure 46, which was connected to the shaker head that had been rotated on its mountings to provide horizontal, lateral Z and Y axis input forces.

The test fixture was secured to a horizontal slip table to accommodate the movement of Ya-21U during the actual 7-min sinusoidal and random vibration sweeps from 5 to 2000 Hz. Calibrated tri-axial accelerometer sensors were bonded to the test fixture and selected Ya-21U components to provide the information required to determine and evaluate the structures' response to simulated launch forces. During the vibration sweeps, force inputs and structural response were monitored and limited by accelerometers bonded to the fixture and to the upper plenum of the reactor assembly.

Low test levels were applied initially to energize the test fixtures, test article, sensors, and data acquisition system to assure that all systems and data channels were functional and calibrated. Higher test levels were applied after a review of the initial test results.

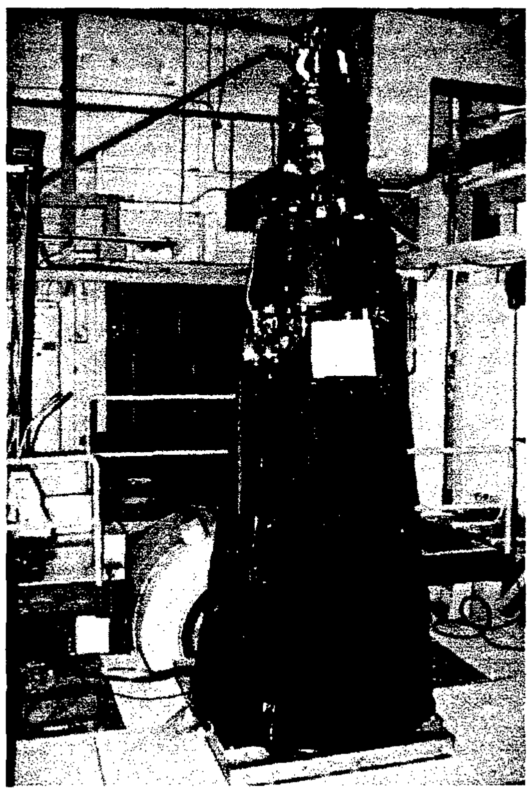


Figure 46. Ya-21U on vibration test fixture.

4.4.2 Lateral Vibration Tests

The first test to be conducted was a sine sweep vibration test in the lateral Z-plane at the specified test levels. The second vibration test was a lateral random frequency sweep.

4.4.3 Axial Vibration and Shock Tests

Axial vibration and shock tests were performed with Ya-21U and the fixture arranged vertically above the electrodynamic shaker head and supported by elastic slings. This arrangement unloaded the shaker head and accommodated the unrestrained movement of Ya-21U in the X-axis vertical direction. As before, vibration sweeps, force inputs and structural response were monitored and limited by accelerometers bonded to the fixture and to the upper plenum of the reactor assembly.

The vibration test stand was then rotated to the vertical test position and Ya-21U was secured to the test fixture and shaker table. The third test conducted was the vertical sine sweep vibration test at the specified test levels. The vertical random frequency sweep test was the fourth test of Ya-21U.

The vertical shock test was performed after the vibration tests using the same electrodynamic vibration shaker to simulate the anticipated pyrotechnic environments of final separation of the spacecraft from the boost vehicle and extension of the boom. The fifth test consisted of a half-sine shock input along the vertical axis.

Sensor data were recorded, displayed, printed, and provided by the data processing equipment of the mechanical test facility. NOTE: Details of the mechanical tests and results are presented in Section 5.

4.5 TEST OPERATIONS FOR THERMAL VACUUM TESTS #9 -#13

4.5.1 Thermal Vacuum Tests after Mechanical Tests

Evacuation of the vacuum chamber was begun of October 18, 1994. Vacuum chamber pressure was reduced to $5x10^{-5}$ torr on October 20, 1994. This was a relatively short period for cold outgassing compared to the expected 3-4 days. The TISA heaters and EM pump were energized on October 20, 1994 to begin hot outgassing of Ya-21U and the new heaters. On November 1, 1994, after two weeks of outgassing, the slow startup was begun.

When NaK outlet temperature exceeds 300°C (573 K), the cesium exhaust line throttle valve must be cycled fully and positioned at 0.6 torr. During cycling, the throttle valve was very difficult to turn. Discussions with Russian Specialists indicated there were two probable causes for this difficulty. There could be cesium oxide contamination of the throttle valve that was caused by air incursions through the cracks in the cesium exhaust line, or the valve could have been damaged by the shock and vibration test. Since cesium exhaust temperatures were at 200°C (473 K), it was decided to try valve cycling again when the exhaust temperatures exceeded 300°C (573 K).

In the early morning hours of November 2, 1994, the UPS-MG indicated a loss of the rectifier. The emergency diesel generator (EG) was started and shifted immediately to maintain constant power on the electrical supply bus. After an hour of EG operation on the load bank, the 50 Hz

power was transferred back to the UPS-MG and the UPS-EG was shutdown, because there was no obvious cause for loss of the rectifier.

On November 5, 1994, Ya-21U started producing power. When output current reached 30 A, helium was evacuated from the interelectrode gaps of the TFEs and the operating characteristics of the converter work section and individual TFEs were observed to be normal.

Operation of the cesium throttle valve continued to be very difficult at an exhaust line temperature of 300°C (573 K). TISA power was held at 80 kW until Russian Specialists from CDBMB in Russia were contacted and further guidance requested.

On November 7, 1994, TISA power was increased to 85 kW and the output voltage was set at 20V for comparison with the data obtained during tests #7 and #8. The comparison indicated that actual cesium pressure was ~0.8 torr. When the cesium throttle valve was cycled, no changes were observed in output power. However, the mass spectrometer indicated an increase in oxygen whenever the valve was cycled. It was decided to cycle the throttle valve hourly until some affect on output power was observed. Several hours later, a change was observed and the valve was reset to a pressure setting of 0.6 torr. At this set point, converter output power matched previous data for a converter output voltage of 20V.

TISA heater power, output converter voltage, and cesium throttle valve were maintained at the same levels for ~3 days to observe output power. During this period, output power decreased very slowly and then stabilized. Power optimization tests were begun at this point to support the conclusions that cesium oxides had contaminated the cesium vapor throttle valve.

Volt-ampere characteristics were completed at cesium pressure settings of 0.3, 0.4, and 0.5 torr. Shortly after beginning optimizations at a cesium pressure setting of 0.6 torr, a load bank cable across the output of Ya-21U failed. Test operators began a normal cool-down of Ya-21U. During the cool-down, a current ammeter of the TISA heater subgroup failed and caused a rapid shutdown of Ya-21U. Repairs were completed within two days and preparations were begun for test #10.

4.5.2 First Rapid Startup and Steady State Performance

The first simulated orbital startup of Ya-21U in the U.S. was performed on the morning of November 15, 1994.

When helium was evacuated from the TFEs during the rapid startup, Ya-21U output current reached 14 A in accordance with established procedures. Immediately thereafter, the output current decreased to 0 A instead of increasing steadily, as expected. When helium evacuation was stopped, output current started increasing again.

In accordance with recommendations of Russian Specialists at ~50 min after startup, helium evacuation was begun again when the output current reached 50 A. During the second helium evacuation, output power increased steadily, as expected.

The initial increase in output current was attributed to the vaporization of a small quantity of cesium that had condensed in the cesium supply system during the previous shutdown of Ya-21U. The condensed cesium had "flashed" to vapor during the initial evacuation and was discharged before the cesium supply system had reached an operating temperature that would produce sufficient vapor to sustain a stable preset cesium pressure. Future simulated orbital startup procedures were revised to begin helium evacuation from the cesium supply system and TFEs at ~40 min after initiation of the startup sequence.

Approximately 4 hr after startup, Ya-21U power output was stable at a TISA heater power of 85 kW. At this time, converter volt-amp characteristic measurements were made at a cesium pressure setting of 0.6 torr and repeated at 0.7 and 1.0 torr for comparison with data obtained before the mechanical tests. Measurements were also made at a cesium pressure setting of 0.4 torr to compare data from before and after the rapid startup.

After the optimization tests, the cesium throttle valve was cycled fully open and back to 0.4 torr to investigate the previous effects of cesium oxide formation in the valve. It was evident during valve cycling that the converter work section output power had increased for the same throttle valve setting. Again, the accuracy of cesium throttle valve was deliberated by Russian and U.S. specialists and a decision was made to investigate its accuracy during the next thermal vacuum test of Ya-21U. Test #10 was completed and Ya-21U was cooled to ambient temperatures.

Thereafter, a data analysis group was formed from TSET personnel to analyze test results obtained during tests #9 and #10. The group included the following: Oleg Izhvanov from the Russian Scientific Industrial Association "LUCH"; Valerie Sinkevich, from Central Design Bureau for Machine Building; Dmitry Paramonov and Ben Wernsman form University of New Mexico; Frank Wyant, from U.S. Air Force Phillips Lab; Glen Schmidt, from New Mexico Engineering Research Institute; and Chris Schreiber, and Dave Luchau from TEAM Specialty Services, Inc.

4.5.3 Second Rapid Startup and Steady State Performance

The objectives of thermal vacuum test #11 were provided by the Ya-21U data analysis working group. It was decided to start test #11 with another simulated orbital startup for comparison with the previous startup of test #10. The second rapid startup was performed on the morning of December 6, 1994. All conditions were normal and similar to the first rapid startup. After completion of the startup, output power optimizations were repeated by conducting volt-amp characteristic measurements at 95 kW and 105 kW with cesium pressure settings of 0.3, 0.4, 0.5 and 0.6 torr. Additional volt-amp characteristic data were taken at 95 kW with cesium pressure settings of 0.7, 1.0, 1.3, 1.7, and 2.0 torr for comparison with previously recorded.

A step decrease in Ya-21U output power was observed between tests #9 and #11. This decrease was attributed to the thermal cycle between run #10 and #11.

As cesium pressure settings were changed with the cesium throttle valve during power optimizations, it was observed that output power did not change, as expected. At this point it was determined that cesium throttle valve settings did not provide an accurate indication of cesium supply pressures. Ya-21U test #11 was discontinued and all data were provided to the Ya-21U data analysis group for evaluation and recommendation for future tests.

4.5.4 Assessments of Cesium System Performance

After an in-depth review of Ya-21U's performance, the data analysis group recommended thermal vacuum test #12. During this test, the cesium throttle valve would be closed completely to permit cesium system pressure to reach the maximum possible at the optimum voltage and a TISA heater power of 105 kW.

A normal startup of Ya-21U was conducted on February 15, 1995. TISA power was raised to 105 kW on February 19, 1995 and allowed to stabilize. When stable, volt-amp characteristic measurements were made, as done previously. Maximum output power was achieved at a load voltage of 26VDC. These conditions were maintained for ~140 hr before a valve on the cesium evacuation system failed during an adjustment to obtain a mass spectrometer reading.

A high pressure alarm in the cesium evacuation line to the TFEs indicated a leak was occurring in the valve. The leak was isolated immediately. Subsequent investigations revealed that the valve being adjusted had a hairline crack in a bellows. The test was terminated and a cool-down of Ya-21U to ambient was completed.

The data analysis group prepared the plan for continuation of the cesium system assessment tests as repairs were being made to the leaking cesium evacuation system valve. The plan required a slow startup of Ya-21U to a TISA power of 105 kW that would be followed by a 200-hr wait at maximum converter output power. Thereafter, output power optimizations of Ya-21U would be performed at TISA power levels of 95 kW and 105 kW with cesium pressure settings of 0.4, 0.5, 0.6, 0.7, 1.0, 1.3, 1.7, 2.0, and 2.3 torr. Ya-21U would then be shutdown and prepared for a third and final rapid startup.

On February 28,1995, a slow startup of Ya-21U was begun and stabilized for a period of 200 hr at a TISA heater power of 105 kW at maximum converter output. After the 200-hr test, output power optimizations were performed at cesium pressure settings of 0.4, and 0.5 torr. When the cesium pressure setting was increased to 0.6 torr, converter performance became erratic and maximum output power occurred at a load voltage of 24 V. Just 24 hr before, the maximum output power had occurred at a load voltage of 30V!

The erratic and unpredictable performance of Ya-21U's converter output power indicated conclusively that the cesium pressure calibration of the cesium system throttle valve was no longer valid. Cesium vapor leakage from the cesium system through leaks in individual TFEs was significantly greater than through the calibrated throttle valve. Thereafter, power output optimizations were performed with the cesium throttle valve fully closed. Results of these optimizations were compared those obtained with specific cesium pressure settings in Ya-21U

test #11. Based on the most recent optimum output power of Ya-21U's converter, the volume of cesium vapor leaking from its TFEs was equal to or greater than that through the throttle valve at a cesium pressure setting of 4.0 torr.

As a result of more thorough analyses of previous Ya-21U performance tests, it was postulated that a reoccurring cold spot could exist in the cesium supply system between the cesium source and TFEs due to thermal cycling. This was based on the observation that at a power level as high as 105 kW, Ya-21U still required ~6 hr for its converter work section to stabilize completely.

On March 23, 1995, helium was added to the cesium supply system to increase its pressure to observe the effect of an inert gas addition on the performance of the TFEs. The voltage of the three TFEs providing current to the EM pump increased immediately when the helium was added and returned to the previous level when the helium was evacuated. The same effect was observed during subsequent additions and evacuations of the inert gas. After completion of the helium additions to the cesium supply system, Ya-21U was cooled down to prepare for the 3rd rapid startup.

4.5.5 Third Rapid Startup of Ya-21U

A third rapid startup was performed on March 24, 1995 to identify variances in output power that were occurring because of thermal cycling and potential formation of a cold spot in the cesium supply line to the thermionic converters. The performance of Ya-21U was normal with a slight decrease in output power at a TISA power level of 85 kW. TISA power was then raised to 105 kW and allowed to stabilized for 8 hr. A volt-amp characteristic test was performed and the maximum output power was determined to be 22 V. This setting of the load was maintained for 48 hr to observe and compare converter output performance.

Thereafter, volt-amp characteristics were determined at a TISA heater of 95 kW with the cesium throttle valve fully closed. TISA power was then increased to 105 kW, temperatures stabilized, and volt-amp characteristics determined. No significant change was observed. At this point, testing was limited to a "maximum" cesium pressure and no new data could be gathered from Ya-21U. The data analysis group recommended shutdown of Ya-21U. The final cool-down of Ya-21U was begun and ended on March 29, 1995.

The thermal vacuum system evaluation testing of TOPAZ-II Ya-21U had ended.

4.6 CHECKOUT OF NAK, CESIUM AND GAS CHARGING SYSTEMS

Pre-test checks of the NaK, cesium, and gas charging included electrical checks of equipment and instrumentation connections inside the vacuum chamber; a functional test of the cesium pressure sensor, and operational check of cesium evacuation line heaters and thermocouples. All Baikal test stand support systems were operated in accordance with previously proven Baikal test stand operating procedures.

Evacuation of the vacuum chamber began on October 8, 1995 and leak checks were completed satisfactorily. However, when the mass spectrometer was place on line, a leak was discovered between valves #2.26 and #2.27. Evacuation of the TFEs was begun and continued for 48 hr until the Baikal test stand vacuum chamber pressure had decreased to $<1x10^{-4}$ torr.

4.6.1 Leak Testing and Outgassing of NaK Charging System

Pump down and evacuation of the NaK charging system began on November 8, 1995 and by November 14, 1995, pressure in the charging system had stabilized at $<5x10^{-6}$ torr. A 1-hr cold static pressure check revealed no leaks and heatup of the charging system was soon thereafter. The NaK charging system was heated slowly to temperatures ranging between 350°C and 600°C (623K and 873K), depending on the location of the NaK component.

The final static pressure leak test of the NaK charging system was completed satisfactorily after temperatures had been maintained for 12 hr at a pressure $<5x10^{-6}$ torr,.

4.6.2 Leak Testing and Outgassing of Cesium and Reactor Evacuation Systems

Evacuation of the cesium and reactor evacuation systems began on October 13, 1995. When pressure in the cesium evacuation system decreased to $<5x10^{-5}$ torr, the cesium evacuation system was heated to a temperature of 350°C-550°C (623K-823K). On October 17, 1995, after the cesium evacuation system was outgassed, the piping from the REU to the TOPAZ II was heated to 350°C-550°C (623 K-823 K) during a 7-day period.

Between October 18 and Oct 23, 1995, three circuit breakers for heaters EH20, EH21, and EH 22 and a heater controller malfunctioned and required replacement.

On October 24, a 1-hr static pressure leak check was performed satisfactorily after outgassing for ~4 hr with internal reactor evacuation piping at temperatures of 350°C-550°C (623K-823K) and pressure $<5x10^{-6}$ torr. Thereafter, internal reactor and cesium evacuation piping heaters were cooled down and secured. Outgassing of the reactor evacuation block was commenced on October 25, 1995 and continued until completion of the radiator electric heater performance test on October 26, 1995.

Additional outgassing of the reactor evacuation unit and the cesium block was conducted during outgassing and leak testing of the NaK charging system conducted from November 6 - 17, 1995. A static pressure leak check of the cesium block was completed satisfactorily on November 16, 1995. The first static pressure leak check of the reactor evacuation unit was attempted on November 16, 1995 and failed. Outgassing was continued until November 17, 1995 when 2-hr static pressure leak test was completed satisfactorily.

4.6.3 Leak Testing and Outgassing of Gas Charging System

On October 10, 1995, preliminary static pressure leak checks, using argon, were conducted on the volume accumulator fill line, CO_2 manifold, and He manifold at a pressure of 3 atm. During the static pressure checks, no change was observed in the gas pressure or vacuum chamber pressure, indicating that the piping was leak-tight. Pump down and evacuation of the gas systems were begun on October 16, 1995 and continued through completion of the radiator electric heater performance test on October 26, 1995. Additional evacuation and leak checks were performed on the gas system during the NaK charging system outgassing tests from November 15-17, 1995.

4.6.4 Functional Checkout of Radiator Electric Heaters

Operational checks of the oil and air transformers used for the NaK fill system were completed on October 24, 1995. The radiator electric heaters were energized on October 25, 1995 and maintained at 1.9 kW to permit the vacuum chamber pressure to recover from the heater outgassing. A hot calibration check of the cesium pressure sensor was conducted satisfactorily during this period.

4.7 LESSONS LEARNED DURING TEST OPERATIONS OF YA-21U SYSTEM

The lessons learned during one modal test; eight thermal vacuum tests before mechanical testing; mechanical vibration and shock tests; and five thermal vacuum tests that followed mechanical testing were many - too many to cite specifically by the Ya-21U evaluation test report. However, several lessons-learned resulted from the requirement for expedient, extensive and intensive transfer of Russian thermionic system technology to the U.S. They were:

- TSET operations personnel were unable to assimilate in a one-year period the 20+ years of Russian experience and information that were needed to prepare, operate and evaluate the Baikal test stand, facility support systems and Ya-21U. Initial Ya-21U tests and characterizations were performed rapidly "by-the-book" without realizing that longer periods of time were needed to allow the thermionic work section and cesium system to stabilize. The quality of data obtained was diminished by the quantity of data produced.

- Mechanical testing of Ya-21U was performed by the SNL with TSET personnel observing the actual tests. With the exception of the modal tests, no previous mechanical tests of a TOPAZ-II system had been performed or observed by SNL and/or TSET personnel. Ya-21U was subjected to excessive mechanical test conditions. Note: An engineering structural system mockup, EH-41, was available and should have been used for checkout of the mechanical test equipment and/or for structural testing.

5.0 SYSTEM TEST RESULTS

5.1 INTRODUCTION

The rationale for performance of Ya-21U tests and a summary of the results and evaluations are presented in this Section 5.0. The tests included: a modal test, the first 1,000-hr thermal vacuum system test and subsequent tests, mechanical vibration and shock tests, and final thermal vacuum tests. The various test measurements and test arrangements are also described.

The modal test of Ya-21U was performed to determine the system's response to low-level vibrations and shock forces. The modal test provided low frequency response information that was needed for design integration and prediction of system's structure to the launch forces expected during the previously planned flight demonstration of the nuclear space power system and electric propulsion spacecraft.

From August 30 through October 16, 1993, Ya-21U was operated at temperature for more than 1,000 hr in the Baikal test stand thermal vacuum chamber at the TSET Laboratory.

The 1,000-hr test was performed to evaluate Ya-21U's performance at operating conditions, to obtain data for design of several system modifications, and to determine the response of the system to external inputs. In addition, the test provided operational performance data to support the previously planned flight demonstration.

Results of the sine and random vibration and shock tests of Ya-21U at the SNL facilities confirmed the vibration modes obtained during previous low-level modal tests. The extended duration vibration sweeps also demonstrated the robust design of the system's structural components and durability of Ya-21U TFEs to withstand launch forces without a single TFE failure even after numerous thermal cycles, more than 3,000 hr of high temperature thermal vacuum test operation, rapid startups and emergency shutdowns.

The results of thermal vacuum tests after the mechanical tests provided an opportunity to evaluate oxygen intrusion into the cesium system and interelectrode gaps of TFEs and the effects on Ya-21U performance.

5.2 TEST PLANS AND EXPERIMENT REVIEWS

Ya-21U tests and experiments were reviewed and evaluated before they were conducted the first time. The reviews and evaluations provided information to TSET operators about proposed tests and experiments and helped to reduce the number of thermal cycles on Ya-21U. TSET management was also required to obtain prior approval from Russian INERTEK management for tests and experiments performed on Ya-21U by TSET. (Luppov #28)

5.3 MODAL TEST RESULTS

The structure was excited from 3 to 64 Hz. The first system mode was just above 20 Hz, while the highest system mode was about 55 Hz. Although there were many local modes in the frequency range of interest (up to 56 Hz), 6 modes were significant. They were the first and second bending modes (in orthogonal pairs), the first torsion mode and the first axial mode. Table 24 lists the frequencies and damping of several modes (some local) obtained from the test data. Table 25 lists the modal parameters at specific modes.

When collecting data, the coherence functions along with frequency response functions were observed. The multiple coherence function was very near one (1) at all significant resonances. This indicated that measured outputs were due to measured inputs. Good coherence also indicates that major nonlinearities were not being exercised. Some modal shape plots are illustrated by Figure 47.

By shaking at low levels, the linear extraction algorithms were able to obtain results that fit the data very well. Final fixed base modes could be predicted accurately from a finite element model that was correlated with this data, with the assumption that it included the seismic mass and air bags in the model. (Mayes #20)

5.4 THERMAL VACUUM TEST RESULTS

Ya-21U system thermal vacuum tests included the following:

- Comparison of Russian and US resistance temperature detector (RTD) characteristics
- Thermal mapping and examination of subsystem thermal characteristics
- Operation and performance studies of the control drum drive actuator
- Electrical characteristics versus reactor core outlet temperatures
- Characterization of sensor signals
- Operating point adjustment evaluation
- Radiated, electromagnetic emission evaluation
- Source impedance, transient response, and noise measurements
- NaK system integrity demonstration
- TFE leak testing
- Work section grounding
- Mechanical vibration and shock testing
- Work section and TFE performance assessments after mechanical testing
- Cesium system contamination and reduced power assessments

Table 24. Test geometry node locations (inches).*

Location	Test Node	X-axis	Y-axis	Z-axis
	358	22.72	0	101.38
Truss near base	359	-11.36	19.68	101.38
	360	-11.36	-19.68	101.38
	364	20.58	0	136.5
Truss mid section	365	-10.29	17.83	136.5
	366	-10.29	-17.83	136.5
	373	12.82	7.4	182.67
Shield base	375	-12.82	7.4	182.67
	376	-12.82	-7.4	182.67
	378	12.82	-7.4	182.67
	390	9.16	9.16	202.86
Shield top brackets	391	-3.35	12.51	202.86
	393	-9.16	-9.16	202.86
	394	3.35	-12.51	202.86
	97	6.33	6.33	210.86
Reactor bottom brackets	98	-2.32	8.65	210.86
	100	-6.33	-6.33	210.86
	101	2.32	-8.65	210.86
	321	6.19	0.00	236.86
Reactor near top	322	0.00	6.19	236.86
	323	-6.19	0.00	236.86
	324	0.00	-6.19	236.86
	340	30	0	94.35
Seismic mass	341	-15	25.98	94.35
	342	-15	-25.98	94.35
	521	10.56	12.25	172.67
Cesium block	522	6.25	12.25	176.98
	523	1.94	12.25	172.67
	501	-4.53	4.5	117.75
Bottom tanks	502	-4.53	-4.5	117.75
	503	6.47	1	131.88
	511	-4.53	4.5	158.17
Top tanks	512	-4.53	-4.5	158.17
	551	26	0	96.75
	552	13	22.52	96.75
Radiator manifold	553	-13	22.52	96.75
	554	-26	0	96.75
	555	-13	-22.52	96.75
	556	13	-22.52	96.75

• 95.75" is considered the base of the truss

Table 25. Modal parameters.

Mode #	Frequency (Hz)	Damping %	Description
1	20.3	0.5	First Bend Y
2	20.9	0.9	First Bend X
3	26.0	0.1	First of Many Cesium Block Modes
4	27.7	0.5	Cesium Block Lateral X
5	31.7	0.8	First Torsion
6	33.8	0.2	Small Tank Bounce
7	35.7	1.2	Second Bending Y
8	36.7	1.1	Second Bending X
9	37.2	0.6	Cesium Block
10	42.7	0.6	Cesium Block
11	43.8	1.1	Radiator Torsion
12	44.2	0.7	Cesium Block
13	55.5	0.5	First Axial

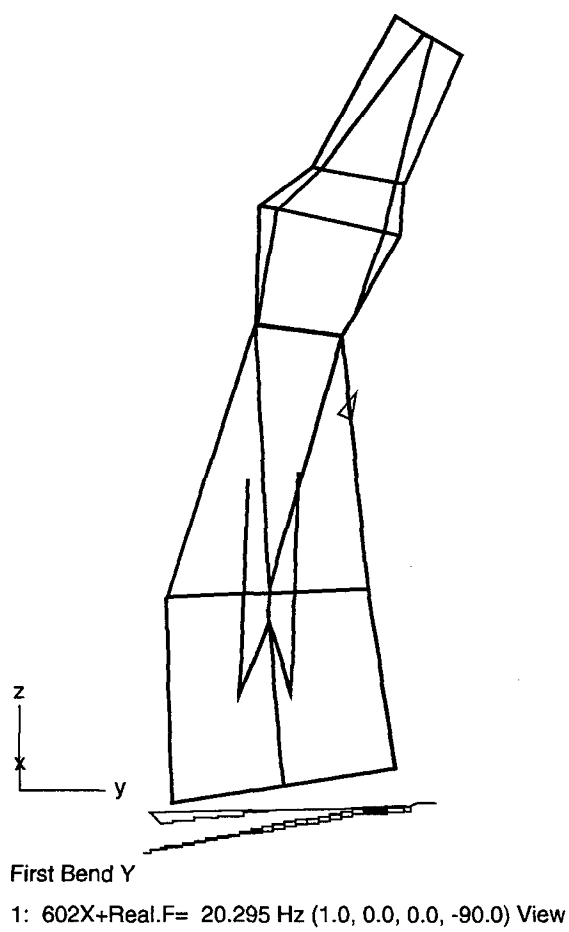


Figure 47. Ya-21U modal shapes.

5.4.1 RTD Sensor Comparison Measurements Test and Results

This Ya-21U test compared signal output characteristics of U.S.-made RTD sensors installed on the lower radiator collector to the currently installed Russian RTDs. They were located close to the three Russian RTDs for direct comparison and correlation of their response during the startup, steady state, and shutdown phases of the system test. (Wyant #25)

Unforeseen problems limited the amount of useful data obtained from the U.S. RTD experiment. The data indicated failures of the U.S. RTDs early in the test. One U.S. RTD failure, indicated by very low voltage measured across its signal leads, was caused by a short circuit. The other two U.S. RTD failures were indicated by open circuit conditions between signal leads. After the test, the vacuum chamber was opened to examine the condition of the U.S. RTDs. The examination disclosed that the positive signal lead on RTD #1 had shorted to the radiator collector, but was otherwise in good working condition, and RTDs #2 and 3 were crushed (RTD #2 was completely powdered and RTD #3 was split into two pieces) probably due to thermal expansion of the collector during Ya-21U heat-up at the beginning of the thermal vacuum test.

The U.S. RTDs had performed as expected until external factors caused failures. Thus, the U.S. RTDs should still be considered for future applications of space power systems. The fragile design of the RTDs required special care during mounting to protect them from severe mechanical forces and shocks and prevent inadvertent shorting of the signal lead wires.

5.4.2 Thermal Mapping Test and Results

The thermal mapping experiment examined the thermal characteristics of different Ya-21U subsystems to enable modeling of the integrated system and monitored temperatures at selected positions on the cesium vapor supply line to the reactor cesium plenum. (Taylor #23)

Twenty-nine K-type TCs were placed at various positions on Ya-21U to monitor subsystem temperatures during the 1,000-hr thermal vacuum test. During the test, TISA heater power was varied from 0 to 95 kW, but most system testing was performed between 75 and 95 kW.

Ya-21U temperatures were kept higher than normal during the test by installation of a stainless steel thermal shield around the lower section of the radiator. NOTE: Caution should be used when comparing Ya-21U test data with the thermal shield installed to test data with the thermal shield removed.

Thermal mapping temperatures were monitored by the DAS and saved at a rate of approximately 1/min. The temperatures were monitored in real time so data problems could be noted and resolved. Data collection was done automatically every minute the DAS was operating. Approximately 18 megabytes of data were collected during the 1,000-hr test.

All temperature indicators performed as expected during Ya-21U startup. When current to the EM pump was increased, NaK coolant flow increased and the differential temperature of the radiator decreased. Then, some anomalies appeared when TISA heater power and system

temperature were increased. As TISA heater power increased, temperatures of the inlet and outlet pipes were expected to increase equally. Actual temperature increases of the two inlets differed by ~17°C (17K), while actual outlet temperature increases differed by ~14°C (14K). The maximum differential between inlet pipe temperatures and outlet pipe temperatures occurred at a TISA heater power of 95 kW.

The anomalies were thought to be associated with locations of the water-cooled heat sinks required to cool the automatic control drum drive during system testing in the Baikal test stand vacuum chamber. The TC, TM03, located on the NaK outlet pipe below the water-cooled heat sink, experienced periods when its temperature was lower than temperatures of other TCs located on the upper manifold. It was proposed that NaK flowing through this pipe was also cooled by the water-cooled heat sink. The result was a colder temperature at the manifold TC than was predicted.

Another unexpected result was the temperature difference between the Russian Ya-21U reactor outlet TC and the U.S. TC at the inlet to the upper manifold of the radiator. The temperatures were expected to be very close to each other. However, when the TISA heater power of the Ya-21U was increased to 90 kW, the temperature difference between the Russian and U.S. TCs approached 70°C (70K), with Russian TCs always indicating higher temperatures.

U.S. thermocouples located at the outlet of the EM pump and Russian thermocouples installed in the reactor outlet pipe were used during analysis of the temperature differences between the NaK coolant inlet and NaK coolant outlet of the reactor,. Table 26 provides the average of the two NaK inlet temperatures and two NaK outlet temperatures to determine the differential temperature of the reactor core coolant.

Table 26. Reactor core differential temperature.

TISA Power Level kW	Average Outlet Temp., K	Average Inlet Temp., K	ΔT (Outlet-Inlet) K
75	732	627	105
80	744	636	108
85	754	641	113
90	767	650	117
95	778	657	121

During the 1,000-hr test of Ya-21U, inlet temperatures of the EM pump were observed to be higher than outlet temperatures. Two explanations for this observation were: (1) temperature data from four TCs on the EM pump may be corrupted by the intense magnetic field surrounding the pump because the TC wires were unshielded, and (2) temperature data from four TCs were correct and the EM pump was a heat sink. The second explanation was supported because the EM pump was secured to the top of the radiation shield by four 7-mm diameter bolts and was physically isolated from the Ya-21U system. If heat transfer through the bolts was neglected, heat entering the system at the EM pump was from NaK coolant, ohmic heating of the EM pump by the supply current, and radiated heat from components surrounding the EM pump. Heat

leaving the EM pump was by conduction through the EM pump power cables and by radiation to the colder components and space surrounding the EM pump.

More in-depth analyses of test data than would have occurred otherwise were performed because of an unexpected EM pump temperature differential and the influence of the automatic control drum drive, water-cooled heat sink. Further investigation is required to explain the above observations.

The temperature of the pipe T-flange section of the cesium vapor supply line was of interest during the thermal mapping test. The pipe at this point was thought to be colder than the rest of the supply line because of its exposure and distance from heat sources. Six TCs were placed along the cesium supply line and cesium block to monitor temperatures and temperature gradients.

Repositioning of several thermal mapping TCs was recommended to investigate the anomalies of this test. The sample rate of the thermal mapping data channels was changed to eliminate problems encountered with the large data files and allow more data correlations to be made. Thermal mapping data provided insight into the thermal response of Ya-21U and may be used to produce and refine system performance models.

5.4.3 Control Drum Drive Operation and Performance Study Results

A study was performed to determine the affects on sensor signals caused by operation of the control drum drive and to determine whether high system temperatures affected the operation of the drive. (Wyant #29)

The control drum drive was operated during the system test, and measurements were made of sensing circuits and sensor signals by observing and noting the characteristics of oscilloscope traces and peak-to-peak voltages. The operations were performed after ~200 hr and again at ~400 hr during the 1,000-hr test of Ya-21U. Electrical connections were made at the 32 W feed-through on the Baikal test stand vacuum chamber, which permitted drive motor actuating signals to be sent and monitored locally at the control drum operating console. Sensor signals were monitored at test terminals in the main terminal cabinet located in the TSET control room.

Equipment used to monitor and log the control drum drive, sensor signals, and signal characteristics included the Russian manual operating console for the drive system and the U.S. digital voltmeter and oscilloscope used to monitor sensor signals.

The Ya-21U sensors included TCs and RTDs to monitor system temperatures, pressure gauges to monitor condition of several gas systems, voltage monitoring of the EM pump, and current output from the TFE working section. The effect of control drum drive operation on each type of sensor was studied separately.

The peak-to-peak voltage values read prior to, during, and following operation of the control drum drive remained in the low millivolt range for the five Ya-21U TCs monitored for noise and on two of the Ya-21U RTD circuits. Operation of the control drum drive caused very little effect on the TC sensors; the effect on the RTD sensors was insignificant.

Virtually no effect was noted on four of the Ya-21U pressure sensor circuits. The peak-to-peak voltage readings taken prior to, during, and following operation of the control drum drive were in the low millivolt range.

There was no effect on the EM pump peak-to-peak voltage readings during operation of the control drum drive. During the second test operation of the control drum drive, a 5-millivolt increase on the TFE working section current monitor was observed. High system operating temperatures did not affect operation of the control drum drive during the 1,000-hr Ya-21U test.

With one possible exception, operation of the control drum drive did not affect the primary sensor circuits of Ya-21U and operation of the control drum drive was not affected by high temperature operation, as well. During follow-on tests, baseline peak-to-peak voltage signals on Ya-21U sensor circuits were measured during operation of the control drum drive and prior to system heat-up.

5.4.4 Electrical Characteristics versus Core Temperature Tests and Results

The effects on Ya-21U parameters caused by varying reactor core temperatures for specific TISA heater power levels were determined by this test. The initial system conditions were as follows: TISA heater power, 90 kW; cesium pressure, 0.8 torr; and EM pump voltage, 0.32 V. Reactor core temperatures were varied by changing the EM pump current, which in turn changed the NaK coolant flow rate through the reactor core. During this test, the EM pump was operated between 0.32 and 0.45 V and provided a NaK flow rate of ~1.1 to 1.4 kg/s. Changes in NaK coolant flow were made in 0.01V steps every 10 min. All the data required for this test were obtained 10 min after changing pump voltage. All parameters were monitored with existing sensors and instrumentation. Ya-21U parameters recorded during the test are listed in Table 27.

During the test, all parameters responded as expected and no significant effects on the output power of the reactor system were observed, as indicated by Figure 48. The total change in working section voltage was less than 0.1V and for working section current less than 0.5 A.

Optimum TFE collector temperature for Ya-21U was ~600°C (873K). At a reactor outlet coolant temperature of 600°C (873K), a small change in collector temperature had little or no effect on the TFE working section output power. A change in reactor inlet and outlet temperatures of 6°C (6K) resulted in a negligible change in collector temperature and working section power. A similar experiment performed previously by Russian specialists concluded that changing EM pump power and NaK coolant flow had little or no effect on working section output. (Schreiber #30, Dakermanji #31)

Table 27. Ya-21U parameters monitored during electrical characterization test.

Parameter	Description	Units
V_{emp}	EM pump voltage	V
I_{emp}	EM pump current	A
21.07	Reactor outlet coolant temperature	°C
21.10a	Reactor inlet coolant temperature	°C
ΔT_{core}	Reactor outlet minus inlet coolant temperature	°C
T_{ave}	Reactor average coolant temperature	°C
V_{ws}	TFE working section voltage	V
I_{ws}	TFE working section current	A
P_{ws}	TFE working section power	kWe
ΔT_{emp}	EM pump outlet minus inlet coolant temperature	°C
P_{tisa}	TISA heater electrical power to reactor	kW
P_{cs}	Cesium pressure in reactor cesium plenum	torr
93.01	Vacuum chamber pressure	torr
93.03	Cesium pressure in cesium evacuation system	torr

5.4.5 Signal Characterization Measurements and Results

This test was performed to identify electrical noise during Ya-21U operation, to verify accuracy of measured data, and to evaluate the significance of signal interference associated with the noise. Specific sensors monitored for noise characteristics included TCs, RTDs, pressure transmitters, and voltage sources. Sensor characteristics measured included direct current voltage levels, RMS voltage levels, and noise amplitude. All measurements were made at terminal block contacts in the main terminal cabinet, located in the TSET laboratory control room. Table 28 lists the sensors monitored by type, identifying number, and primary function. Figure 48 indicates the location of each sensor on Ya-21U. (Wyant #32)

Data were obtained by measurement probes in contact with appropriate terminals for the sensors in the main terminal cabinet. A disadvantage with this method was the potential influence of other circuits connected in parallel with the sensor circuit being tested, such as the TSET DAS circuits. Sensor signals were measured by DC and AC voltmeter probes and an oscilloscope (DC voltage and noise AC peak-to-peak amplitude). A digital voltmeter was used and the output voltage across the terminals was logged in DC and RMS (AC) measurement data.

An oscilloscope was used to measure DC offset voltage levels for comparison with digital voltmeter readings. The oscilloscope was also used to measure the magnitude of any overlaying noise on the base signal. Voltmeter and oscilloscope data were recorded and evaluated.

Except for one condition, noise interference was not a problem on the primary system sensors measured. The EM pump voltage measurement may be affected by noise where noise sources were one-tenth of the base signal levels while at system power. The EM pump voltage was not a

critical system parameter, and noise on this circuit was insignificant for determining the system's health. The signal-to-noise ratios for other sensors were measured in the 20-60 decibel range.

Future sensor characterization measurements of Ya-21U should consider the following: (1) all sensors and signals that provide useful information for application of the TOPAZ-II system technology should be identified and characterized, especially sensor and signals used by the reactor control unit and spacecraft, and (2) the effects of other circuits connected in parallel with the diagnostic equipment on measured data should be determined and characterized.

Table 28. Ya-21U sensors measured for noise effects.

Type	ID No.	Purpose
TC	21.07a	Reactor coolant outlet temperature
	21.08a	Reactor coolant outlet temperature
	21.07	Reactor coolant outlet temperature
	21.08	Reactor coolant outlet temperature
	21.10a	Reactor coolant inlet temperature
RTD	21.01	Radiator lower collector temperature (U.S.)
	21.02	Radiator lower collector temperature (U.S.)
	21.03	Radiator lower collector temperature (U.S.)
	21.16	Radiator lower collector temperature (Russian)
	21.18	Radiator return leg temperature (Russian)
	46.02	Control drum drive temperature (Russian)
PG	07.01	Reactor helium gas pressure
	26.01	Reactor moderator oxidizer gas pressure
	08.01	Reactor shield helium gas pressure
	30.01	Coolant volume accumulator argon gas pressure
	46.03	Control drum drive gas pressure
EMP	67.01	EM pump voltage
WS	67.04	Working section current monitor (voltage)

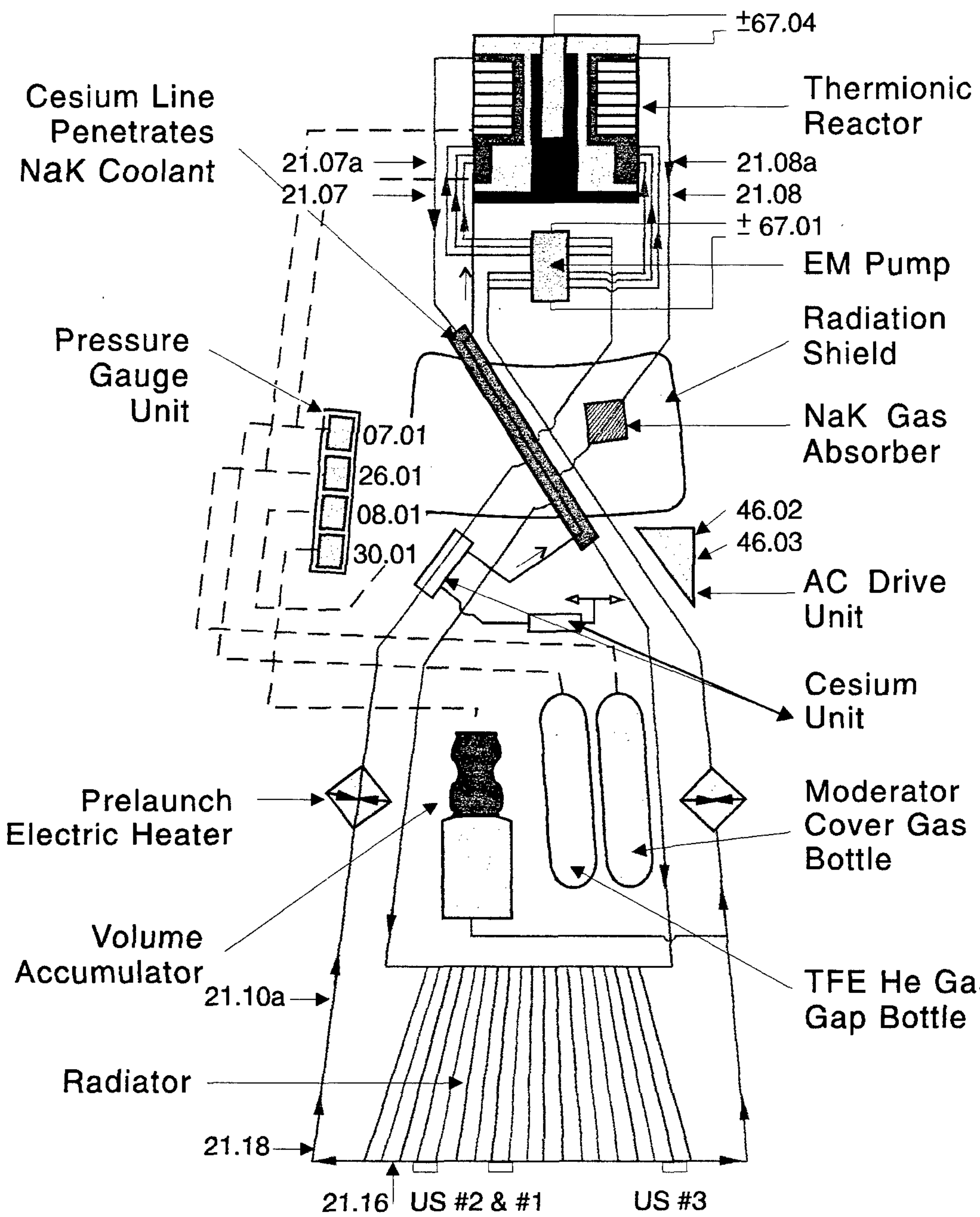


Figure 48. Ya-21U system and sensor locations.

5.4.6 <u>Operating Point Adjustment Evaluation Test and Results</u>

This test provided baseline data specific to Ya-21U to enable performance during its operating lifetime. This test also provided an opportunity for TSET operations personnel to become familiar with the performance characteristics of Ya-21U and for comparison with the V-71 system. This system test did not require special equipment. System test conditions were achieved by TISA heater power adjustments, setting load bank resistance, and cesium vapor pressure adjustments. (Luchau #7)

Operating evaluations were performed during the 1,000-hr system test with the NaK coolant outlet temperature in the normal operating range of ~500 °C (773 K) at three time intervals: 200, 700, and 900 hr of operation. The system test operations included varying TISA heater input power level in 5 kW steps between 75 and 85 kW. At each power level cesium pressure was varied in 0.2-torr increments, over the range of 0.4 to 1.0 torr. Output voltage was also varied from 18 to 30 V in 2-V increments by changing the resistive load to determine the maximum electrical power output. TFE working section output power data were evaluated at each of the key points indicated above.

Cesium vapor pressure settings were varied in increments of 0.1 torr over the range of 0.4 to 1.0 torr. After each pressure setting, the system was allowed to stabilize for at least 90 min prior to recording TISA heater power, cesium pressure, reactor outlet temperature, and working section output voltage and current. At each cesium pressure set-point, the TISA heater power was adjusted in 5-kW increments between 75 kW and 95 kW. After each power adjustment, the system was allowed to stabilize for at least 15 min prior to taking data on key system parameters.

At each TISA heater power level, the working section output voltage was adjusted in 2-V increments between 18 and 30 VDC. Working section current was maintained less than 300 A as an operational limit. After each voltage adjustment, the system was allowed to stabilize for at least 5 min prior to taking data on key parameters.

Data collected during the Ya-21U tests indicated that 0.4 torr was the optimum cesium pressure setting and that 30 VDC was the optimum voltage for system power levels. Between measurements taken at 200 and at 700 hr, Ya-21U power output dropped by more than 100 W, in several cases. Some event had occurred between the 200-hr data and the 700-hr data that affected the output performance of Ya-21U. TFE leaks may have occurred sometime during this period. Figure 49 indicates specific changes in output power compared to working section voltage at a cesium vapor pressure setting of 0.4 torr.

The following recommendations were based on the results of the system test. Data should be taken for each power level at a constant cesium pressure setting to minimize the time required to take these measurements. TISA heater power levels should be recorded at the same time to ensure data were consistent with previous recordings.

5.4.7 Radiated Emission Evaluation Test and Results

This test was performed to determine Ya-21U's radiated electric field and potential for impacting sensitive instruments installed on the proposed NEPSTP spacecraft. Non-invasive radiated electric field measurements were made while operating Ya-21U. Four antennas, with a frequency range of 300 kHz to 300 MHz, were installed in the top of the vacuum chamber around the circumference of the Ya-21U reactor. Selected access ports were positioned every 90 degrees with ~1 m radius from the perimeter of the reactor. A Hewlett Packard (HP) spectrum analyzer and plotter were used to acquire and record emission data received by the antennas.

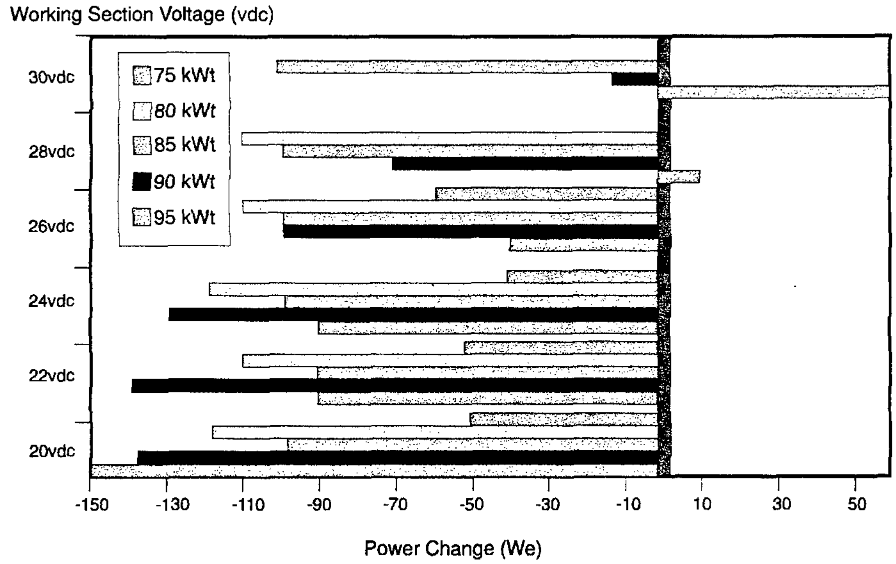


Figure 49. Ya-21U output power change between 200 and 700 hours.

All detected noise peaks were less than -50 dBm in the 1 to 4 MHz range. The -50 dBm was equivalent to 10 nanowatts of power (0 dBm equals 1 mW). The measured noise appeared to originate from sources other than Ya-21U. This level of radiated power would not have an impact on sensitive spacecraft type instruments. The observed low level noise may have been generated by the Baikal test stand vacuum pumps and vacuum chamber controls. (Schwartz #33)

5.4.9 Source Impedance, Transient Response, and Noise Measurements Tests and Results

JHU/APL performed tests on Ya-21U for the following purposes:

- to measure noise (frequency domain and time domain) generated by the system and conducted to output power leads in an effort to determine system response to load transients,
- to measure system impedance,
- to measure impedance of power cables between the system and Baikal test stand chamber,
- to measure leakage resistance between positive and negative power leads to the Ya-21U structure, and
- to characterize output of the TFE working section.

JHU/APL used a Solar 6741-1 current probe connected to the load bank cable from the negative vacuum chamber terminal for the conducted emissions (frequency domain) test. The probe signal was fed to an HP 8568B spectrum analyzer through an HP 8447A amplifier, and the system was controlled by an HP 9836 Series 200 computer. Both narrow-band and broad-band noise measurements were made over the frequency range of 15 kHz to 50 MHz.

Ya-21U noise (time domain) was measured in a 65 MHz bandwidth using a 7A13 differential amplifier plug-in to a Tektronix 7854 oscilloscope. The differential amplifier maintained isolation between instrument ground and system output.

For transient response measurements, a step load change was introduced by switching resistive loads across the Ya-21U output via a transistor switch driven by a function generator. The Ya-21U voltage response was observed on the oscilloscope using the 7A13 differential amplifier.

To measure the Ya-21U system impedance, two 100-A Solar isolation transformers were wired in parallel between Ya-21U and the load. Thus, the full output load current of YA-21U could flow through two secondary circuits and provide a 200-A capability. The primary circuits were wired in series and driven from an HP 4194A impedance analyzer oscillator through a Solar 6552-1A power amplifier and 6220-1A transformer. The resulting AC voltage and current ripple were sensed in the Ya-21U branch of the network by an A6902A optical isolator, the output of which was provided to the impedance analyzer to determine the resulting impedance and phase. Source impedance was measured from 10 Hz to 1 MHz. All isolation requirements were maintained with this system test configuration.

A power line impedance measurement test was performed on the non-powered Ya-21U system by applying an electrical short across the output power terminals of the system. The power line impedance was measured using an HP 4194A impedance analyzer.

Leakage resistances were determined by switching a resistor into the circuit between each Ya-21U power lead and ground, by recording the change in DC voltage with a high input impedance digital voltmeter, and then by calculation of the DC leakage resistance. The test data were collected and displayed by APL using magnetic media, and an HP 7476 plotter was connected to the diagnostic equipment.

The results of the emissions tests conducted indicated that most emissions were generated by the Baikal test stand vacuum chamber, system control, and DAS equipment. No measurable noise was observed on the Ya-21U power bus.

Fast rise and fall times of applied loads caused voltage transients to exceed 30 V at the measurement point outside the Baikal test stand vacuum chamber. This measurement point was ~2.44 m from the Baikal test stand load bank and its 28,000-microfarad capacitor.

The DC source impedance was approximately 0.4 ohm at 70 A. (NOTE: Ya-21U's source impedance was higher than that measured on the V-71 unit: 0.125 ohm at 65 A and 0.25 ohm at 100 A.) Test results did not indicate the expected inductive characteristics of the Ya-21U power cable because a small current-sensing resistor was causing AC measurement errors. Power cable impedance measurements made on the V-71 system indicated the cable looks like an inductor of approximately 2 micro-henrys with less than a 5-milliohm resistance, which was the expected impedance of Ya-21U power cables.

Measurements made in September 1993 on Ya-21U indicated a large resistance variance between the system structure and positive and negative power leads. The calculated leakage resistance to the structure was less than 1 ohm. During the October 1993 tests, APL was informed by Russian specialists that grounding of the reactor data acquisition computer was incorrect and caused the large resistance variance between the system structure and the positive

and negative power leads. Subsequent leakage resistance measurements and the calculated leakage resistance between the system structure and each lead were approximately 32 ohms, which agreed with previous results obtained by Russian specialists.

The large transient response observed by APL during the system tests was caused by the inductance of the power cables between the Baikal test stand load bank capacitors, Ya-21U inside the Baikal test stand vacuum chamber, and the test points. The transient voltage at the Ya-21U terminals should be negligible. During the system tests, transient current amplitude was not increased because there were no test points for monitoring output voltage at the Ya-21U terminals.

The source of the emissions that caused the measured noise were investigated further by APL. If access to the Ya-21U terminals at the 48W connector is available, the transient response test should be repeated to ensure voltage transients at the terminals are known and controlled.

Impedance measurements should be repeated using a Hall effect current sensor instead of the current sensing resistor that affected previous results.

5.4.10 Lessons Learned during Initial Performance Tests

Some tests improved understanding of Ya-21U; for example, Ya-21U does not radiate significant levels of electromagnetic radiation and does not affect sensitive instruments. Furthermore, principal system sensor circuits were not very susceptible to external noise sources, and operation of the automatic control drum drive does not adversely affect signals on sensor circuits, as expected previously. Continued testing of Ya-21U was very beneficial and continued to improve understanding of the unique Russian technology.

Ya-21U tests during the August-October 1993 test period provided interesting learning opportunities. EM pump heat transfer anomalies were encountered during thermal mapping tests. Lower cesium vapor pressures (contrary to U.S. and Russian expectations) produced optimum power levels from the TFE working section; in some cases, measurements of the Ya-21U working section output characteristics were anomalous. The preceding were examples of test uncertainties encountered during initial performance evaluation of Ya-21U.

5.5 MECHANICAL TEST RESULTS

Five mechanical tests were performed on Ya-21U at the SNL vibration test facility during the period of September 6-9, 1994. The tests included lateral Z-axis sine and random vibration tests, axial X-axis sine and vibration tests, and a axial shock test.

5.5.1 Functional Test Results of Test Equipment, Sensors, and Data Acquisition Systems

Prior to each test run a few low level sweeps of the shaker table were performed to check the operation of the accelerometers and the data acquisition system. All instruments performed as expected.

5.5.2 Lateral Vibration Test Results

Ya-21U was set-up for excitation first in the Z-axis, as described previously in Sections 3.6 and 4.4. The accelerometer sensor coordinates were related to the Ya-21U lateral coordinates as indicated by Table 29. The sine-test parameters were those listed in Table 30 with a test duration sweep of ~1 min/axis. Note: The following differences between the test parameters and those used in the actual test were:

1. The input was ramped up instead of using the planned steps.
2. The maximum sweep-rate available from the SNL vibration stand was 0.75 octaves/min which corresponded to a test duration sweep of ~7 min/axis over the frequency range of 5 - 200 hertz. This test duration sweep was substantially longer than was planned or would have been experienced during an actual launch of a TOPAZ-II power system.

The planned random-test test parameters were used in the actual conduct of the test. Sine-test tolerances and response limitations for the sine-test parameters were:

1. A standard test tolerance of ±10% was placed on the test parameters
2. The primary control was located adjacent to the outboard foot of the Z-axis tripod leg, designated instrument #2.

Three additional control accelerometers instruments # 2, #5, and #9 were used to limit the response of Ya-21U to ensure that it would not be over-stressed. Locations of these auxiliary controls are listed in Table 29. The response of these auxiliary controls were limited to less than 6, 9, and 12 dB, respectively.

The random-test tolerances and response limitations for the random-test parameters were:

1. A test-stand tolerance of ±3.0 dB on PSD and ±1.0 dB on the overall level was used.
2. The same primary control used for the Sine-test was used for this test and no additional controls were required.

The lateral-axis sine-test results were:

1. The input level at the base of Ya-21U were notched as illustrated by Figure 50.
2. The fundamental frequency of Ya-21U was 8.8 Hz, as illustrated in Figure 51.
3. The second mode occurred at approximately 27 Hz. The top of the reactor experienced amplification factors (Q) of 26 and 4.5, respectively, as indicated by Figure 52.
4. The amplification factor at the top of the reactor was higher than expected and corresponds to a system damping ratio of less than 2%.
5. The response at the top of the reactor was limited to 12 dB (~4.0 g), as illustrated in Figure 53. Notching of the input was required to prevent over-stressing of Ya-21U and effectively limited the input level to ~0.15 g instead of the 1.0 g specified input.
6. The worst case responses, defined as any response greater than 4.0 g, are listed in Table 31.

Table 29. Relationship of accelerometer coordinates to Ya-21U lateral coordinates

Instrument No.	System Coordinate	Accelerometer Coordinate
1	X, Y, Z	X, Z, Y
2	Y, Z	X, Y ,Z
3	Z	Z, Y, X
4	Y	Z, Y, X
5	X, Z	X, Y, Z
6	X, Z	X, Z, Y
7	Z	X, Y, Z
8	Z	X, Z, Y
9	X, Y, Z	X, Y, Z
10	-- -- --	X, Z, Y
11	X, Y, Z	X, Y, Z
12	X, Y, Z	X, Z, Y

Table 30. Sine vibration test parameters.

Frequency (Hz)	Level (g)
5	0.25
5 - 8	constant slope
8 - 40	1.0
40 - 100	0.9
100 - 200	0.8

Table 31. Worst case response to lateral axis sine vibration excitation.

Location	Axis	Level (g)	Frequency (Hz).
Reactor Top Plenum	Z	4.5	9.3
Bottom of Collector	Y	4.5	48
Cesium Unit	X	5.2	28
Cesium Unit	Y	5.0	25
Cesium Unit	Z	9.0	25
Startup Unit	Z	5.0	25

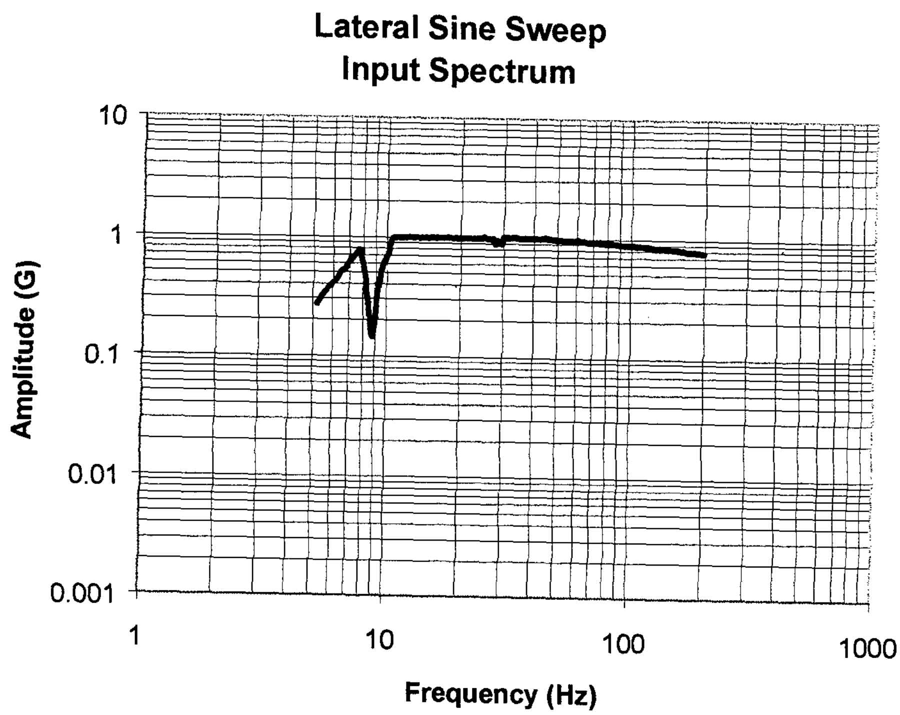


Figure 50. Lateral sine test input.

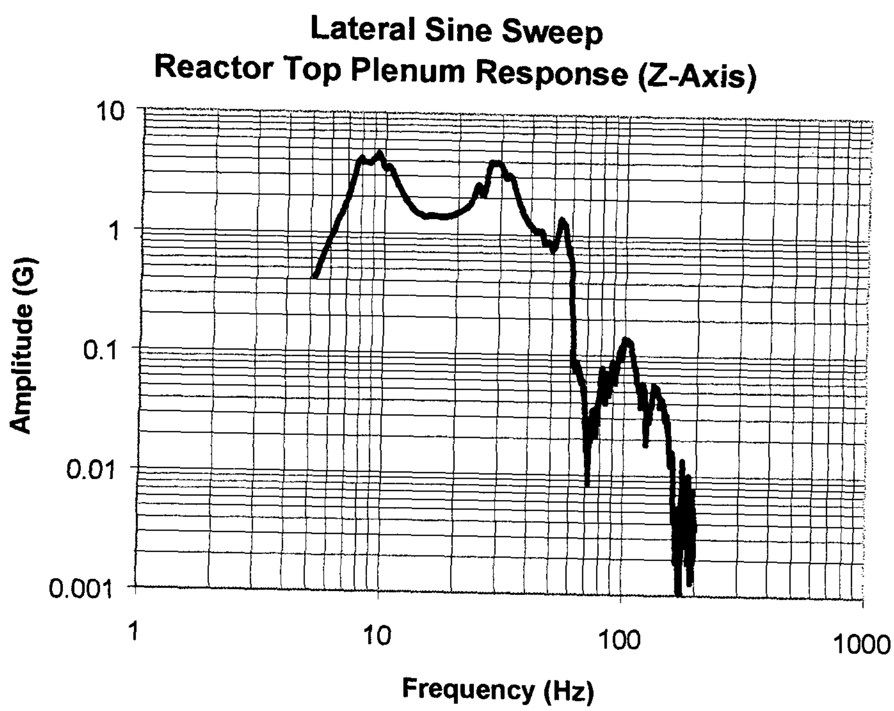


Figure 51. Reactor top plenum response to lateral sine sweep input.

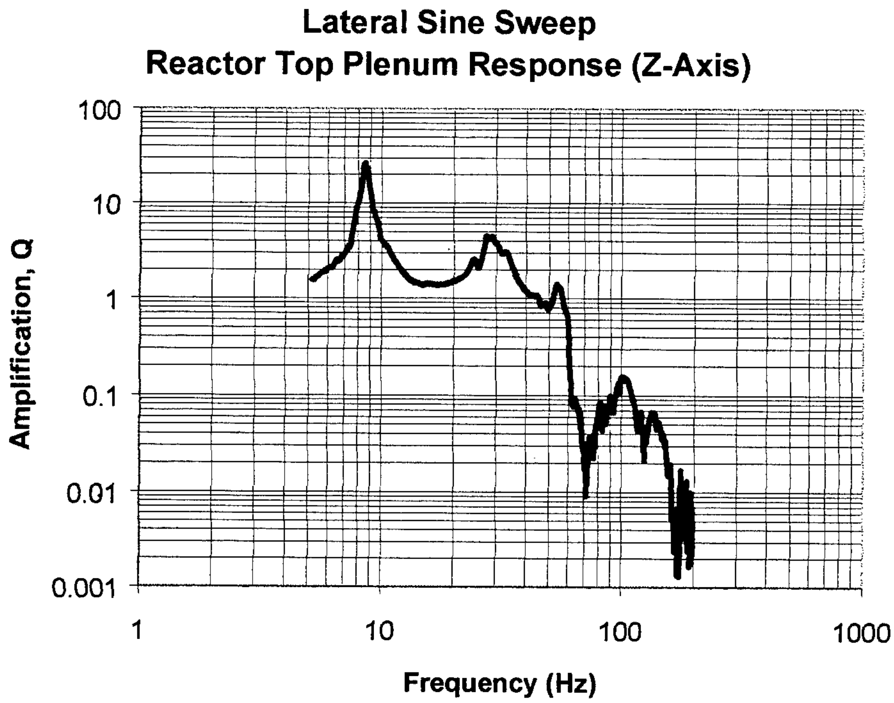


Figure 52. Amplification factors for the reactor top plenum during lateral sine test.

The random-test input at the base of Ya-21U is illustrated by Figure 53 and the results were:

1. Random vibration tests started at 20 Hz. This was well above the Ya-21U first mode of 8.8 Hz and did not influence the response of the system.

2. The second mode did influence the response of Ya-21U at the top of the reactor, as illustrated in Figure 54. This represented a response, in terms of power (PSD) of ~13 dB above the input, in the 30 Hz frequency band.

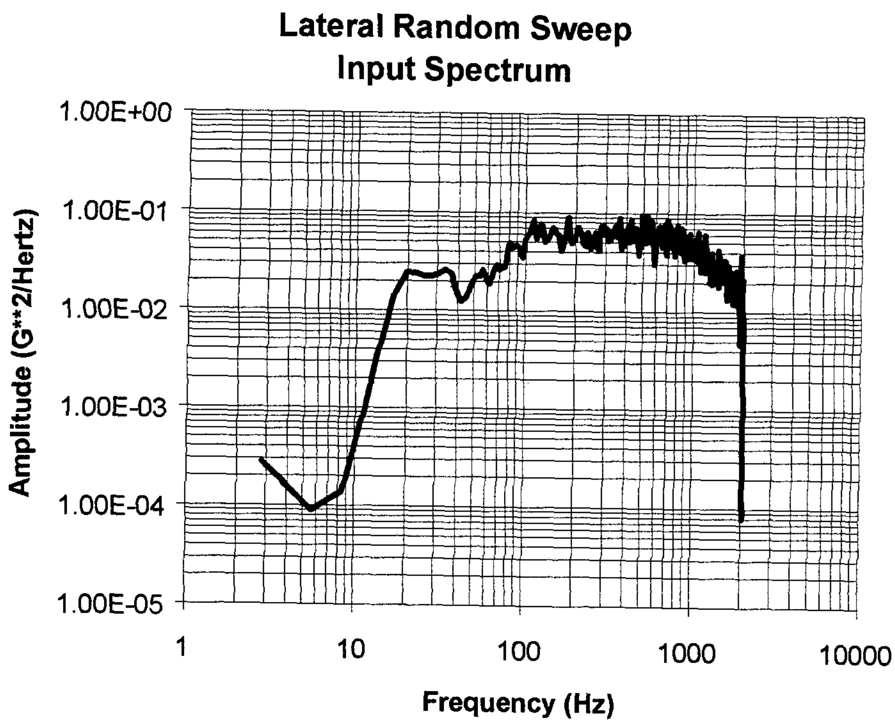


Figure 53. Lateral random sweep input spectrum.

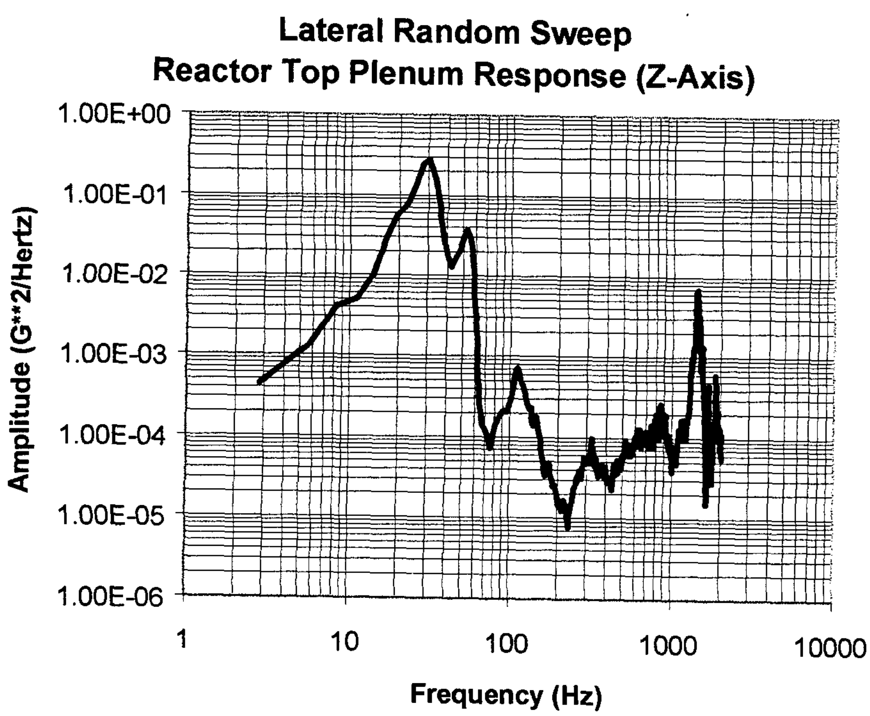


Figure 54. Response of reactor top plenum to random sweep input.

5.5.3 Axial Vibration and Shock Test Results

Accelerometer coordinates were related to the Ya-21U coordinates, as indicated by Table 32.

Table 32. Relationship of accelerometer coordinates to Ya-21U axial coordinates

Instrument No.	System Coordinate	Accelerometer Coordinate
1	X, Y, Z	X, Z, Y
2	X, Y	X, Y ,Z
3	X	Z, Y, X
4	X	Z, Y, X
5	X	X, Y, Z
6	X, Y	X, Z, Y
7	X	X, Y, Z
8	X	X, Z, Y
9	X, Z	X, Y, Z
10	X, Y	X, Z, Y
11	X, Y, Z	X, Y, Z
12	X, Y, Z	X, Z, Y

Axial vibration test parameters and variations were the same as those for the lateral vibration tests.

Test tolerances and response limitations for the test parameters were similar to those for the lateral vibration tests. The exceptions were: the sine vibration responses were not limited and the random test response for instrument #6 was limited to 12 dB.

The vertical axis sine-test results were:.

1. The input level at the shaker head is illustrated by Figure 55 and the response at the base of Ya-21U is shown in Figure 56.

2. This response is the caused by design of the test fixture which extends in the radial direction ~12 in. beyond the shaker head to mate with the tripod legs of Ya-21U.

3. The fundamental frequency of Ya-21U with fixture attached was 38 Hz. The maximum response occurred at the cesium reservoir and vapor supply (cesium block) which had a peak amplification factor of ~11, as illustrated by Figure 57.

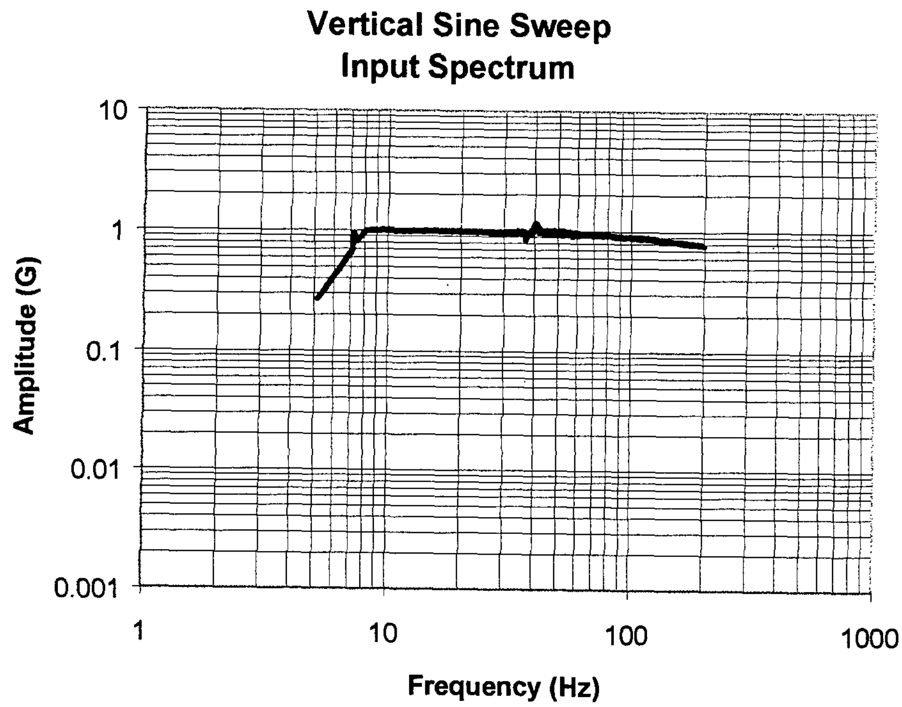


Figure 55. Vertical sine sweep input spectrum.

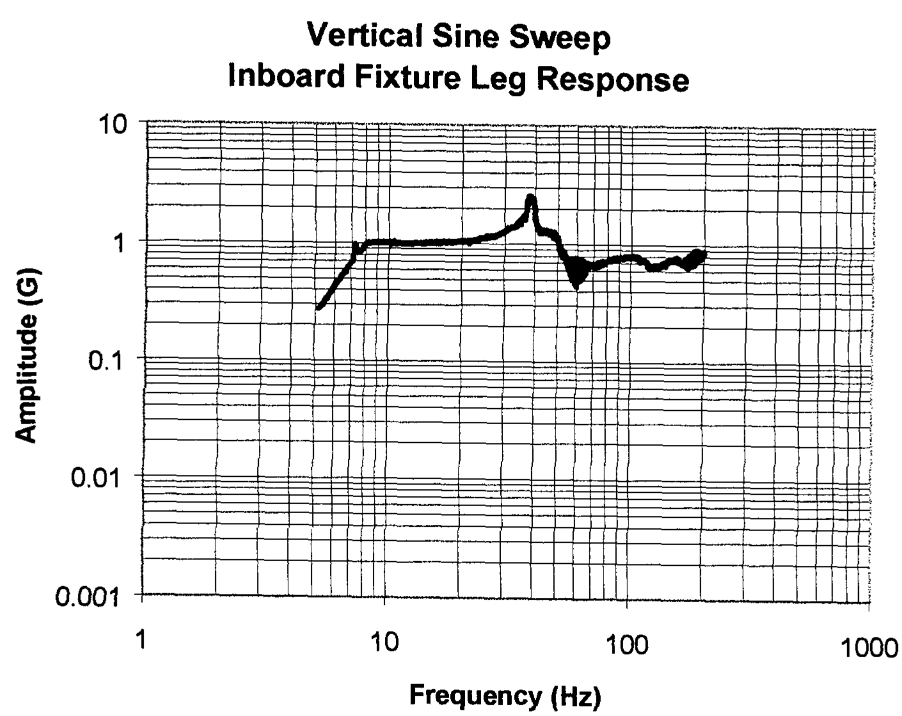


Figure 56. Response of inboard fixture leg to vertical sine sweep input.

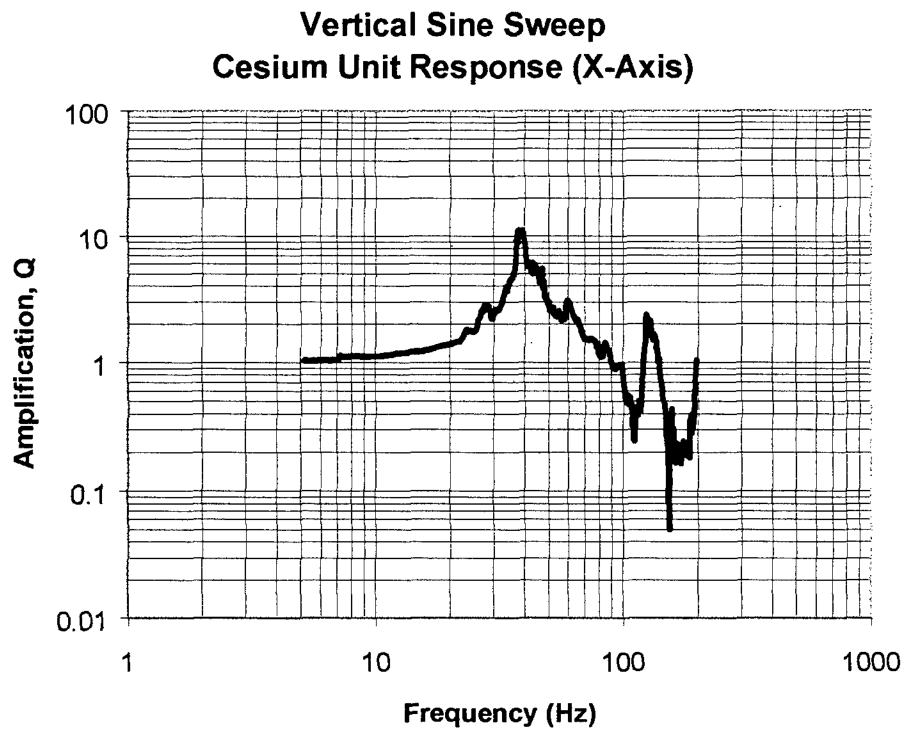


Figure 57. Amplification factors for cesium unit to vertical sine sweep input.

The random input level at the head of the shaker is illustrated by Figure 58 and the response at the base of Ya-21U is illustrated by Figure 59. As before, the difference was caused by the test fixture. The maximum response occurred at the top of the reactor, as illustrated by Figure 60.

A shock was performed on Ya-21U in the longitudinal X-axis. The lateral axis shock test was not performed as previously planned because of limitations of the vibration stand to generate a simulated pulse lead.

The X-axis shock was simulated using a 40 g haversine, 6.5 millisecond pulse that reached an amplitude of 100 g. The maximum response of Ya-21U was ~200 g at 240 Hz. The result of the shock test are illustrated by Figures 61 and 62.

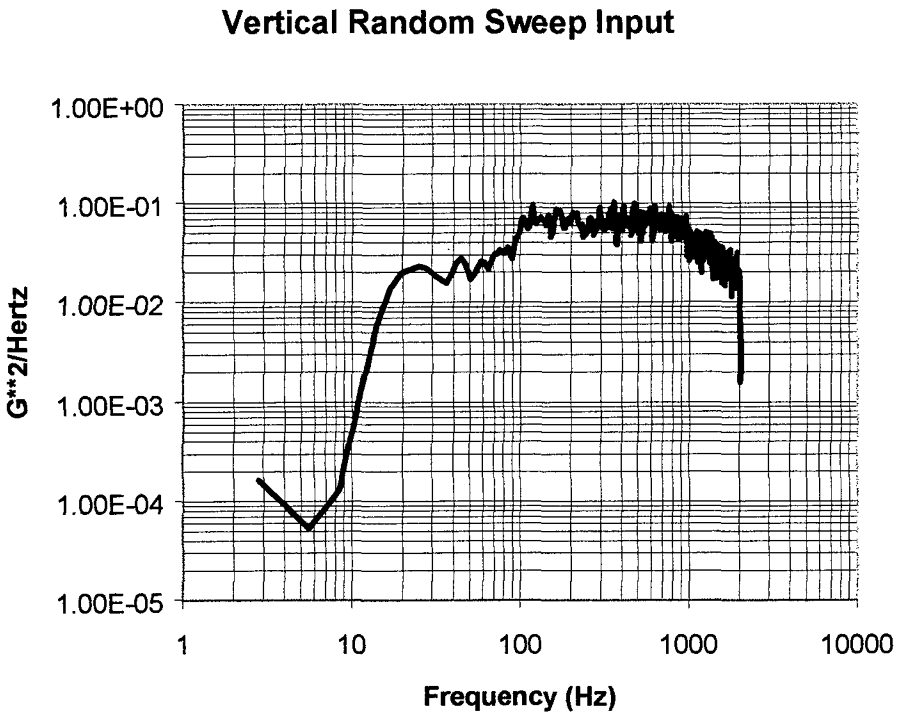


Figure 58. Vertical random sweep input spectrum.

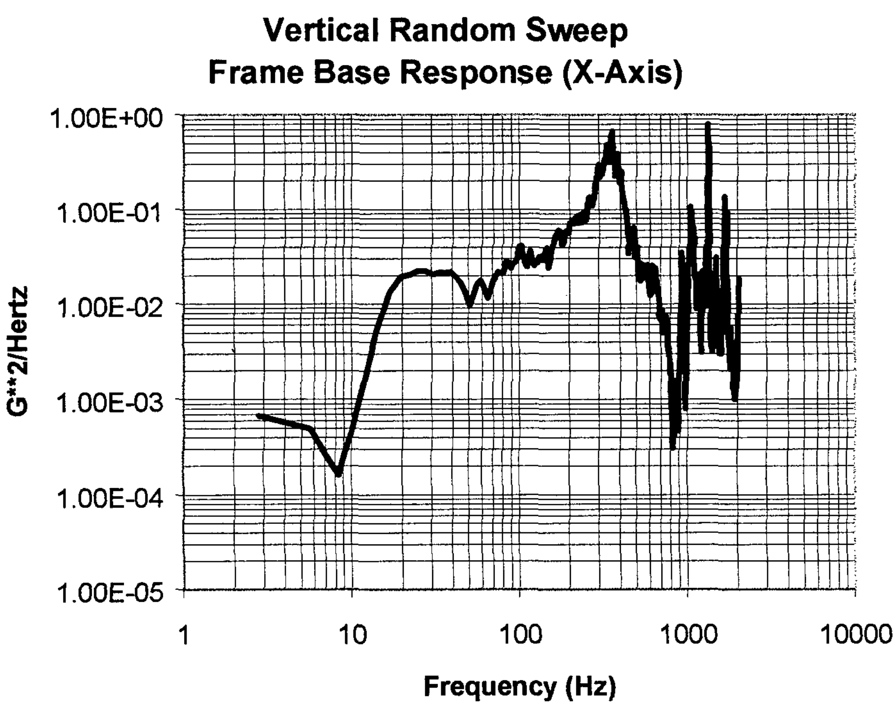


Figure 59. Frame base response during vertical random sweep test.

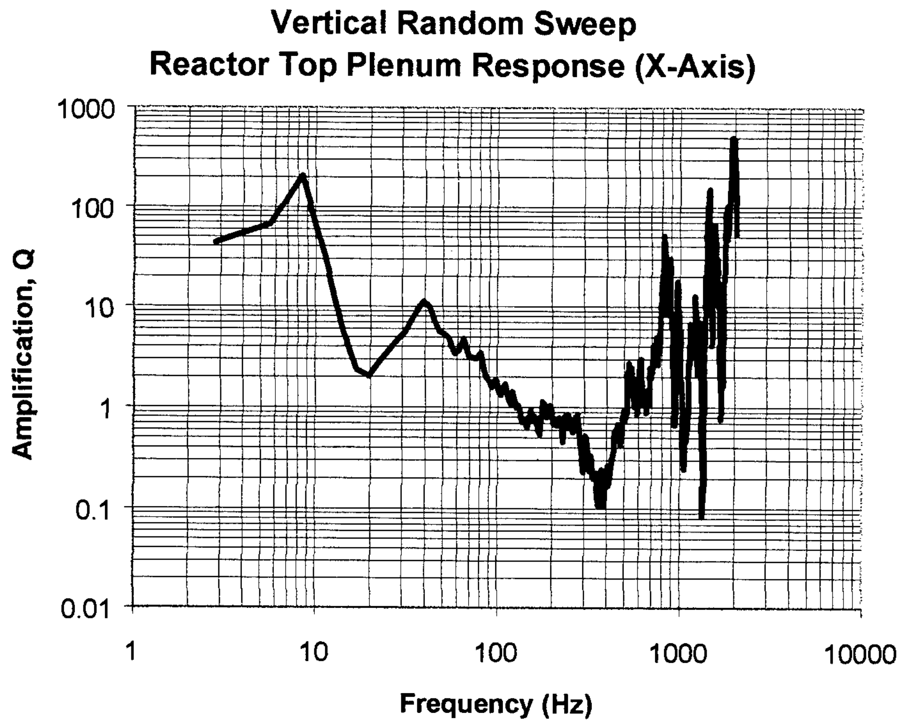


Figure 60. Amplification factors for reactor top plenum response during vertical random sweep test.

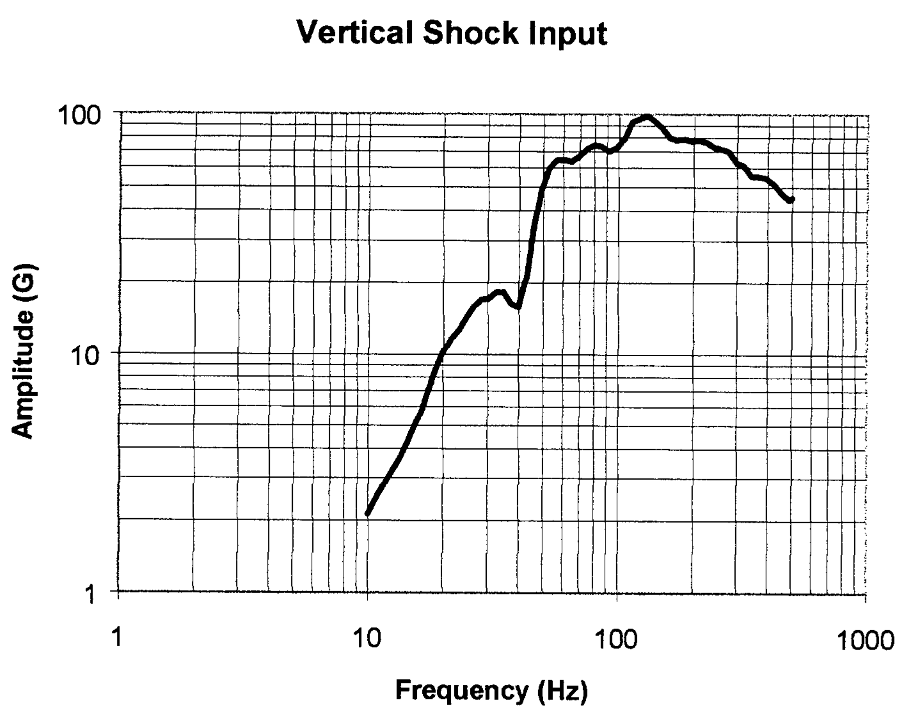


Figure 61. Vertical shock test input spectrum.

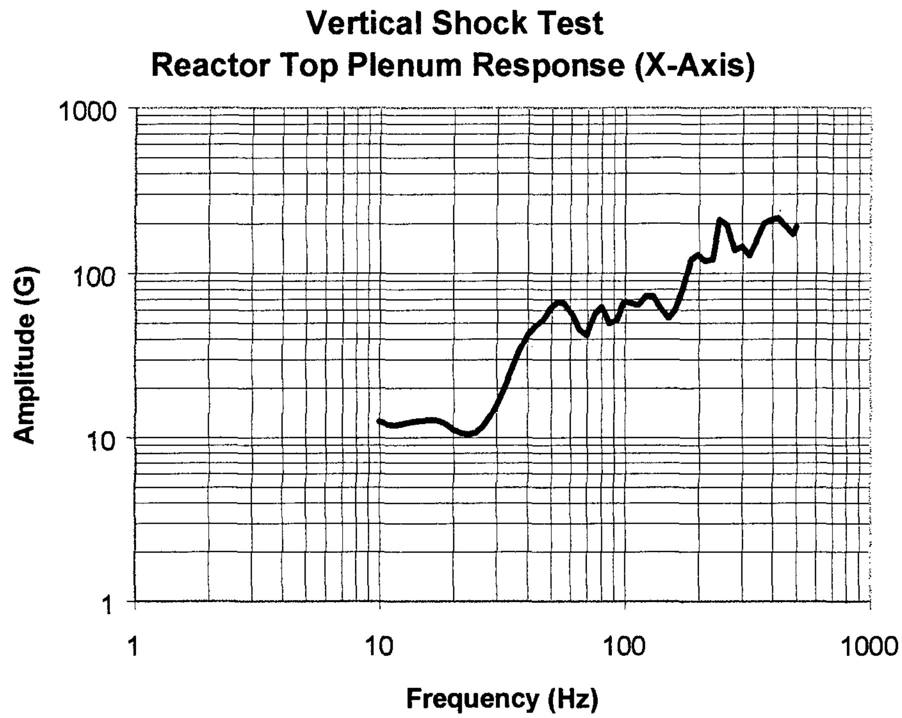


Figure 62. Reactor top plenum response during vertical shock test.

5.6 FINAL THERMAL VACUUM TEST RESULTS

After completion of the shock and vibration tests, Ya-21U was removed from the test fixture, surveyed for beryllium, removed from the SNL vibration facility and returned to TSET. No detectable beryllium was found on the test fixture or Ya-21U.

5.6.1 Inspection and Functional Test Results after Mechanical Tests

After arrival at TSET, Ya-21U was placed in the vacuum chamber of the Baikal test stand. A complete and intensive visual inspection was performed on all reactor components, TFEs, radiation shield, instrumentation sensors, control drum drive motor, NaK piping, EM pump, radiator, expansion compensator, gas containers, and power, control, and instrumentation cables. A leak check of the TFEs was also be conducted, after the nuclear fuel simulators were removed.

No evidence of damage or degradation was revealed by the visual inspection. However, a leak was detected when the Ya-21U cesium exhaust line was connected to the Baikal test stand evacuation line. The leak was found in the cesium exhaust line where it connects to the Ya-21U cesium block. In addition, two small cracks were found in the cesium exhaust line on the cesium block. The leaks were sealed with a shellac compound, provided by Russian specialists.

Subsequently, leak checks of the TFEs were performed. The leak rates for the five leaking TFEs determined to be about the same as was observed prior to the shock and vibration test. No additional TFEs were found to be leaking.

Ya-21U was prepared for thermal vacuum testing after completion of the post vibration and shock test inspections.

5.6.2 Pre-Startup Test Results

Pre-startup electrical resistance measurements of Ya-21U were made on October 19, 1994 prior to the thermal operation. These measurements were taken at ambient temperature, ~18°C (291K). The results are provided in Table 33.

Table 33. Results of resistance measurements of Ya-21U circuits.

Measurement	Reading	Requirement
TISA heater insulation resistance to ground	all ≥21 MΩ	>1 KΩ
TISA heater to TFE cathode resistance	all ≥19 MΩ	>15 Ω
TFE cathode to ground resistance	all ≥311 Ω	>15 Ω
TFE cathode to anode resistance	all ≥423 Ω	>15 Ω

5.6.3 Slow Startup and Performance Test Results

Prior to the slow startup on October 20 1994, the Baikal test stand vacuum chamber was evacuated to a pressure $<1x10^{-5}$ torr, and the TFE interelectrode gap was evacuated to $<1x10^{-6}$ torr and the TFEs were backfilled with helium to ~6 torr. The cesium supply system throttle valve was a cesium supply pressure setting of 0.6 torr. TISA heater power was then increased slowly to maintain a heatup rate of <100°C/hr to minimize thermal stresses on the reactor. At a TISA power of ~70 kW, the TFEs started to produce electrical current. When the output current reached 30A, helium in the cesium supply system was evacuated in 1-torr increments while monitoring the converter output current to verify current increases with each increment. After the TFEs were ignited, TISA power was raised to 85 kW and stabilized to compare the observed performance with previous test results. All aspects of the startup were normal.

At the TISA heater power of 85 kW, Ya-21U converter output power had decreased ~300 W compared to the previous test performed prior to mechanical testing. During power optimization tests, the optimum cesium pressure had increased from 0.4 torr to 1.0 torr and the load voltage for optimum power output had decreased from 30V to 18V.

5.6.4 Rapid Startup Test Results

The following pretest conditions were verified before beginning the first rapid startup test of Ya-21U on November 14, 1994:

- TISA heaters were energized and provided ~1.5 kW of power.
- Ya-21U NaK coolant outlet temperature was ≤60°C (333K).
- Baikal test stand water system was operating and vacuum chamber outlet water temperature was ≤50°C (323K).
- Baikal test stand vacuum system was operating at a chamber pressure of $\leq 1 \times 10^{-5}$ torr.
- Ya-21U cesium system was pressurized with helium at ~4.5 torr and ready for evacuation.
- Baikal test stand load bank was set at minimum resistance (≤0.05 ohm).
- Baikal test stand DAS was operating and storing data at 1 minute intervals.
- AC drive ready to operate and in "zero" position.
- The Baikal test stand DAS and all chart recorders were synchronized in time.
- All critical test-stations were assigned and ready.

All Ya-21U test parameters were checked for conformance with limits given in Reference 1. Along with this, the cesium throttle valve was set to provide a cesium pressure of 0.6 torr.

TISA heater power was increased to 2.5 kW, in accordance with Baikal test stand procedure entitled; *TOPAZ II Power System Startup and Steady State Operations.*

The rapid startup of Ya-21U began when TISA heater power was increased at a rate that matched the power profile, illustrated in Figure 63, that was ~2 kW/min up to 12.5 kW, and 4.25 kW/min thereafter, up to 85 kW. All plant conditions were monitored during the rapid startup; one warning alarm occurred, but conditions did not reach limits for automatic or emergency shutdown.

Helium was evacuated from theYa-21U TFEs when the converter output current reached ~14 A. However, TFE output current decreased to zero during this period. The explanation was that the cesium supply unit had not yet warmed up to the point of producing sufficient vapor to sustain the thermionic conversion process. The working section current of $I_{WS.} \geq 50$ A was obtained in 50 min from the beginning of the startup that agrees well with the requirements and demonstrated the quality of the startup. During the startup and stabilization mode, all the parameters remained within the required safe limits.

Once TISA power reached 85 kW, Ya-21U conditions were stabilized and held for an additional 2 hr, as indicated by Table 34. The DAS data storage frequency was changed to 15 min intervals.

Thereafter, the converter load was changed to provide 20 V and a current of 89A. A graph of the rapid startup test parameters is provided in Figure 64. The plots are normalized to their expected peak values.

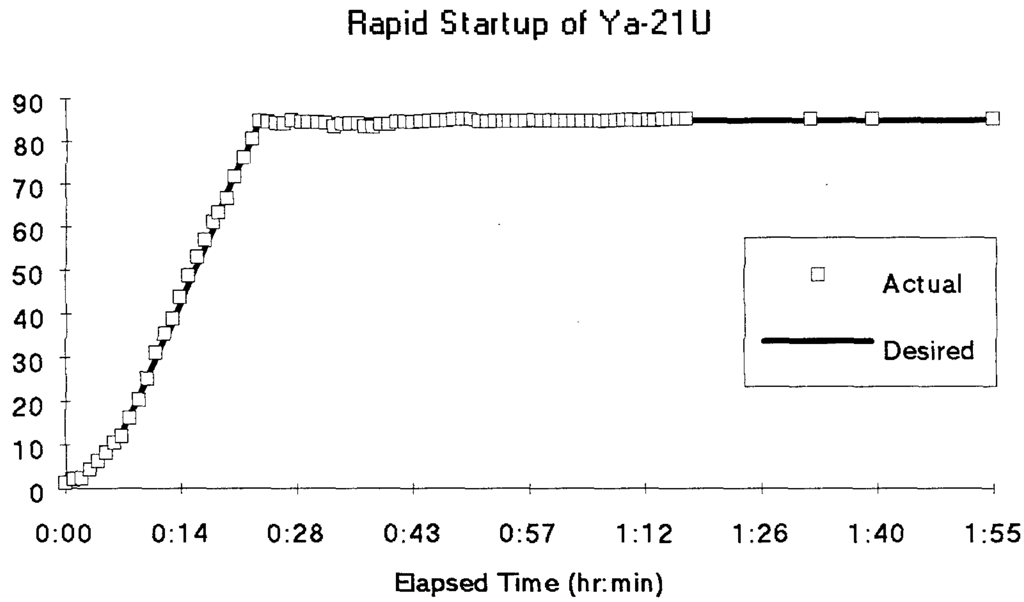


Figure 63. TISA heater power profile.

Table 34. Ya-21U stabilized power mode two hours after startup.

Parameter	Value
N_{TISA} (kW)	85
I_{ws} (A)	195
U_{ws} (V)	8.7
T_{in} [°C(K)]	460(733)
T_{out} [°C(K)]	513(786)

After that U_{WS} = 20 V was set by means of load variation, and the current was set to I_{WS}= 89 amp. A graph of the rapid startup test parameters is provided in Figure 64. The plots are normalized to their expected peak values.

Two additional rapid startups of Ya-21U were conducted. The startup procedures were the same with the exception that helium was not vented from the TFE interelectrode gaps until 40 min following the start of the power rise. The results of these tests are shown in Figures 65 and 66.

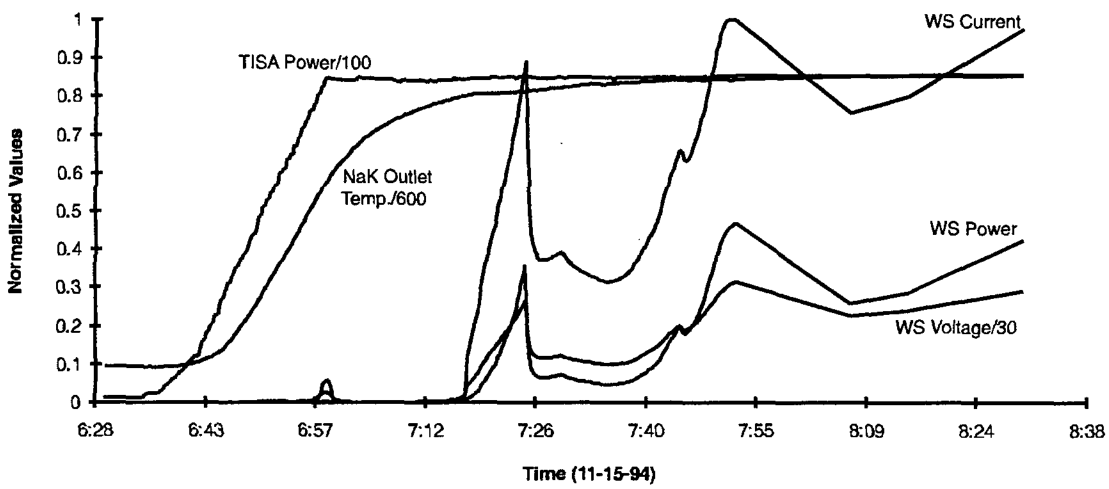


Figure 64. Ya-21U rapid startup test parameters normalized to expected peak values.

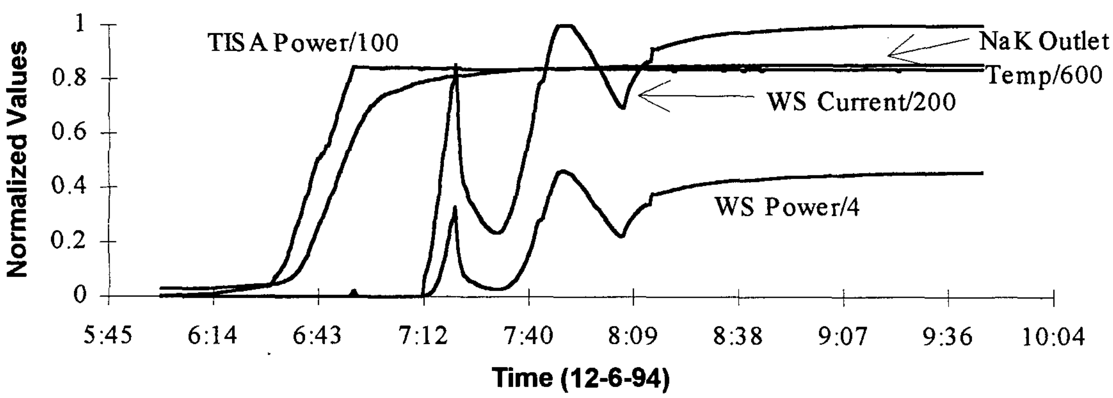


Figure 65. Second rapid startup of Ya21U.

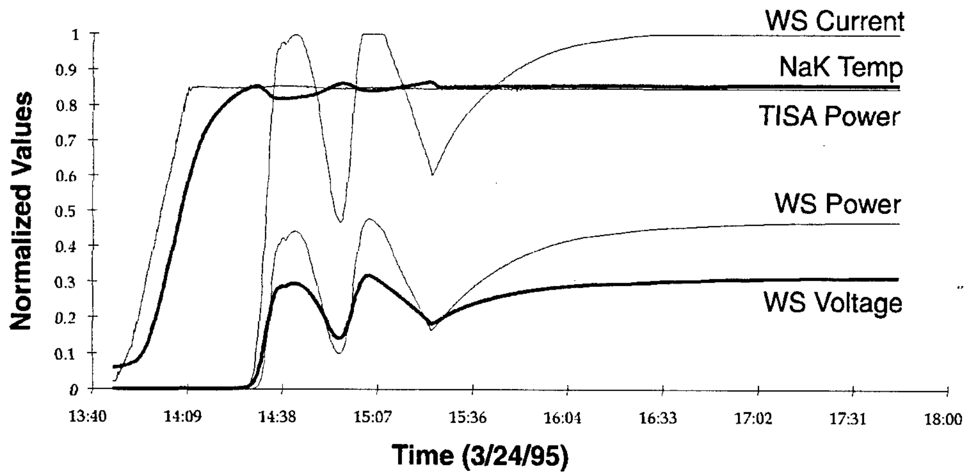


Figure 66. Third rapid startup of Ya-21U.

6.0 TEST DATA CORRELATIONS

6.1 INTRODUCTION

The first U.S. Ya-21U thermal vacuum tests established the system's performance baseline. The tests were precursors to the mechanical vibration and shock tests and subsequent thermal vacuum tests used to evaluate the effects of mechanical stresses on system performance and to determine the system's durability. In addition, the performance shown by other special tests provided insight into the operational characteristics of Ya-21U.

The 1,000-hr thermal vacuum performance test of Ya-21U began August 30, 1993, and ended successfully on October 16, 1994. The main parameters for system evaluation were the following: TISA heater power input, TFE work section power output, and cesium vapor supply pressure setting. One of the most important parameters to monitor during Ya-21U tests was the amount of electricity produced by direct conversion of heat energy.

To compare results of tests performed in Russia with U.S. test results required the Ya-21U output power to be optimized at various TISA heater input power levels and cesium vapor pressures settings. This task was difficult because detailed reports on test conditions of Russian experiments were lacking. Comparisons were made using a TISA heater input power of 85 kW and a cesium vapor pressure setting of 0.6 torr because this was the only reported Russian test condition and data that could be compared with a U.S. Ya-21U system test condition.

According to the Russian summary report of Ya-21U, the optimum output power was 2.16 kWe at 85.6 kW input power, 0.6-torr cesium pressure setting, and load resistance of 0.338 ohms. This compared very closely with U.S. tests that produced an optimum output power of 2.11 kWe at 85 kW input power, 0.6-torr cesium pressure setting, and a load resistance of 0.371 ohms. Extrapolated higher output power levels, based on U.S. system performance test results, indicated Ya-21U would produce ~5.5 kWe at a thermal input power of 120 kW. This system performance level corresponds exactly to previous Russian claims that the TOPAZ II system would produce 5.5 kWe at a reactor power level of 120 kW. The Ya-21U system conversion efficiency, a ratio of electrical output power to input thermal power, was 3.4 % at a TISA heater input power of 95 kW and 0.4-torr cesium vapor pressure setting. When corrected for electrical lead losses at this TISA power, the conversion efficiency would be ~4.0%.

The Ya-21U NaK coolant system performed, as expected, during four power and four thermal cycles from 75 to 95 kW, three rapid startups and three rapid cool-downs from 50 kW, 82 kW, and 95 kW.

The intrusion of oxygen into the cesium system and interelectrode gaps through leaks in hermetic seals of TFEs and the cesium vapor vent line when Ya-21U was exposed to air during system shutdown resulted in a graceful, but increased reduction of output power from the converter work section. Such leaks would not have had the same effect if Ya-21U had been started up and operated during its lifetime in an orbital environment.

6.2 KEY TEST PARAMETERS

During the first U.S. test, all Ya-21U test parameters were limited to those listed by TOPAZ II design specifications and provided by Russian specialists. While conducting the test, the main parameters of Ya-21U were varied within the ranges indicated by Table 35.

Table 35. Range of main test parameters.

Parameter	Range
TISA Heater Input Power	75-95 kW
Cesium Vapor Pressure	0.4 - 1.4 torr
EM Pump Voltage	0.1 - 0.32 V*
Working Section Output Voltage	20 - 30 V
Working Section Output Current	55 - 130 A
Reactor Outlet Temperature	495 - 550°C (768 - 823 K)
Vacuum Chamber Pressure	1 x 10^{-4} - 10^{-7} torr

* During a short duration experiment, EM pump voltage was raised to 0.45 V, however. the nominal range was 0.1 to 0.32 V.

6.3 YA-21U OPTIMIZATION METHODS

During the first thermal vacuum test of Ya-21U, conversion of heat energy was one of the more important parameters monitored. The Ya-21U system work section output power was optimized at various TISA heater power levels and cesium vapor pressure settings to enable comparison of Russian test results to U.S. results. The methods used to optimize system power output and conclusions are presented in the following paragraphs.

6.3.1 Cesium Pressure

During thermal vacuum system tests, cesium vapor pressure in the Ya-21U reactor plenum was controlled by a throttle valve within the cesium reservoir and regulator block on the system. The throttle valve was linked mechanically to a hermetically sealed operator located outside of the vacuum chamber. The cesium throttle valve within the cesium block was calibrated in Russia to vary the cesium vapor pressure directly according to the rotation of the throttle valve stem. The Russian calibration chart for the throttle valve was used to set the cesium vapor pressure because there was no pressure sensor to obtain an independent reading of pressure in the cesium plenum. When the cesium pressure was adjusted, at least 90 min was allowed for the cesium system pressure to stabilize before making other adjustments to Ya-21U.

6.3.2 Voltage of Working Section

The electrical output of the TFE working section was connected to a resistive load bank and a transistive load bank. Resistance in the resistive load bank was varied to adjust the work section voltage and current produced. The transistive load bank was also used to adjust the work section

voltage and was used to stabilize the voltage.. During Ya-21U tests, the work section voltage was changed in 2-V increments from 18 to 30 V for measurement of work section current. After adjustment of work section voltage, Ya-21U was allowed to stabilize for at least 5 min.

6.3.3 Thermal Input Power

TISA heaters provided the thermal input power to the TFEs. Three groups of TISA heaters were each controlled separately to assure the average power of each group did not vary more than 10 % from the average of all 37 TISA heaters. This assured that each of the 37 TFEs was heated to approximately the same emitter temperature for a desired thermal input power level. During this test, the TISA heater power level was increased to a maximum of 95 kW. Steady-state operation of Ya-21U parameters was made at 75, 80, 85, 90, and 95 kW of thermal input power. When the TISA heater power level was changed, 30 min were required to stabilize the new operating parameters.

6.4 DATA ACQUISITION

The Baikal test stand DAS was driven by a 486-66 computer and monitored 192 analog channels. It displayed and logged data to a file acquired during Ya-21U tests. A calibration data curve for each sensor was used for the conversion algorithms for the data acquisition code. Data logging rates were selected by the system test operators, for example: 1/m, 1/5 min, 4/hr, or none at all. The data were stored on a hard disk over a 24-hr period and then transferred automatically at midnight via the communication channel to a main drive on the local area network system. Data from the DAS could be displayed for the operators by several methods. The main display panel provided a tabulated view of all calibrated data. Another display provided a graphical schematic of the complete cesium handling system with essential data displayed at specific sensor locations. This display did not provide all of the data being acquired at the time. Several other custom displays were also available to system test operators.

6.4.1 Sources of Uncertainties

During the 1,000-hr Ya-21U tests, an attempt was made to identify and quantify sources of measurement inaccuracies and special care was taken to characterize and minimize sources and levels of uncertainties in the parameter monitoring system. This task was made more difficult because Russian-built sensors were interfaced with available U.S. DAS hardware.

The principal sources of uncertainty with the TSET DAS included the following:

- Russian Sensor Errors
  Calibration certifications were not provided by Russian specialists for the individual instruments used and monitored. Instead, a calibration curve was provided for a class of instruments, e.g., TCs, RTDs, pressure gauges, etc. In addition, non-linear operating regimes were not provided for any Ya-21U sensors and instruments, which made quantification of their uncertainty questionable.

- Cabling and Connector Errors
  Cabling and connections in the signal path were subjected to external influence, like any other hardwired signal transmission system. Unshielded wires and connectors can act as antenna, subject to excitation by external electromagnetic fields, sneak circuits, and other disturbances. Also, leakage losses can affect the expected levels of uncertainties. Based on data obtained during the Ya-21U Signal Characterization Measurements Test, the estimated level of uncertainty from signal cabling and connectors was ~0.5 %.

- Signal Conversion Errors
  The DAS acquired raw signals, usually voltage or current, and converted them to a digital number and transmitted this number to the DAS computer. This process converted a continuous function into a discrete number, which introduced some uncertainty because there were a finite number of values available for the conversion process. For example, the use of a 12-bit analog-to-digital conversion (ADC) circuit, over the range of 0 to 10 VDC, meant that there were only 4096 (212) discrete values available to represent the full 10-volt range. Thus, converting a signal at any point in time was accurate within 2.44 mV. In addition, settling time affected the accuracy of converted signals because the ADC must scan and convert a number of input signals one at a time. This required a finite amount of time, on the order of milliseconds, to handle each channel.

  The TSET DAS used 4-Hz filtering circuits on input signal lines from Ya-21U. The use of filtering circuits on input signals to the ADC added some uncertainty to the process. The estimated level of uncertainty from the signal conversion process was ~0.5 %.

- Display Algorithm Errors
  After conversion of a raw signal to an equivalent digital number, the digital number was reconverted to usable form for display to the operator in real time and for data logging to a data file for later analysis. In many cases, this was a two-step process. First, the digital number was reconverted back to the equivalent voltage, and second, a conversion was then made, using the instrument's calibration curve, to provide a useful indication of the system's test condition to the test operator. Errors did occur with development of conversion algorithms for display of usable parameters during modeling of rough instrument calibration curves provided by Russian specialists. Estimation of the uncertainties associated with this process was difficult.

Consequently, a conservative value of ±1.5 % accuracy was used to quantify the overall uncertainty of data recorded for the Ya-21U 1,000-hr test. This was the best engineering judgment that could be made at that time.

6.4.2 Problems Encountered during Initial Thermal Vacuum Testing

Some difficulties with the DAS were encountered early in the 1,000-hr operation of Ya-21U. After Ya-21U was brought to power and stabilized, operators noticed anomalous readings from some sensors. Some required tracing short circuits, others required adjustment to re-conversion algorithms, and others were caused by mistakes in signal wiring. Troubleshooting required disconnection of parts of the DAS for some periods of time during continuation of the Ya-21U test and data logging function. Signal dropouts occurred and some signals pegged upscale during these periods of problem solving. The quality of logged data and data displayed for the operators was good enough to assess performance of Ya-21U throughout the test.

Selected time-dependent plots of the Ya-21U main parameter data, accumulated during the 1,000-hr test, are presented in the Appendix and provide a general operating profile of the system test. Because DAS signal problems were noticed and corrected at various times throughout the Ya-21U test, some regions within these plots may contain inaccurate data.

6.4.3 Data Reduction and Analysis

Operational data stored by the DAS were plotted using the TOPAZ Data Analysis Program (TDAP). TDAP enabled users, even without computer experience, to retrieve and plot numerous combinations of sensor data obtained during Ya-21U tests. Many graphical plots were generated and provided using TDAP. The data and graphical plots were stored in the TSET computer files.

6.5 COMPARISON OF U.S. AND RUSSIAN RESULTS FROM FIRST THERMAL VACUUM TEST

Comparisons of U.S. test results with Russian test results were important tasks during TSET. The tasks were made difficult because detailed reports on Russian test conditions and experiments were not available. The Russian document entitled; *Summary Report on Reactor Unit #19 (Ya-21U) Nuclear Power System TOPAZ-II* was the only document that provided specific information on Ya-21U's performance. It provided insufficient information on precise test parameters and explanations for deviations in Russian test results. Comparisons were made at a TISA heater power of 85 kW and a cesium vapor pressure setting of 0.6 torr because they comprised the only Russian data that corresponded with data from the U.S. tests.

The system test of Ya-21U, performed to demonstrate the integrity of the NaK coolant system, required system operating temperatures above 450°C (723 K) for ~1,000 hr. Russian specialists became concerned because high TISA heater power levels would be required, which could cause overheating at the top end of the TFEs due to heat losses from the TISA heater leads above the tungsten heating elements. Russian specialists strongly recommended use of a thermal shield to cover part of the Ya-21U radiator to reduce heat rejected, to reduce TISA heater power, and to increase NaK system temperatures during the 1,000-hr thermal vacuum test.

The Russian specialists were concerned because top sections of Ya-21U TFEs were previously overheated and overstressed during a high power system test, performed in Russia, at 123 kW. This caused the TFEs to be susceptible to mechanical damage due to embrittlement resulting from overheating and over-stressing. Installation of the thermal shield accommodated the requirement for higher NaK coolant temperatures at lower TISA heater power levels.

6.5.1 Working Section Performance

Ya-21U's output power was dependent upon thermal input power, cesium vapor pressure, and load resistance. The optimum cesium vapor pressure setting within the range tested for the first U.S. test was 0.4 torr, as indicated by Figure 67. In Russia, the optimum cesium vapor pressure setting was 0.6 torr. A close examination of Figure 67 indicated the optimum pressure setting to be 0.6 torr, if a 0.4 torr cesium vapor setting had not been examined. This anomaly was thoroughly investigated to determine its cause.

A comparison of Russian and U.S. Ya-21U output power indicated good correlation. According to the Russian summary report, at TISA heater power input of 85.6 kW, 0.6-torr cesium pressure setting, and load resistance of 0.338 ohms, the optimum Ya-21U output power was 2.16 kWe. This agreed with U.S. results; for example: Ya-21U produced 2.11 kWe at a TISA input power of 85 kW, 0.6-torr cesium pressure setting and a load resistance of 0.371 ohms.

The conversion efficiency of Ya-21U was the ratio of electrical output power to thermal input power, illustrated by Figure 68. The maximum conversion efficiency of Ya-21U was 3.0 % at 95 kW input power (not corrected for TISA heater lead losses) at a cesium pressure setting 0.4-torr. Efficiency increased as thermal power was increased until a maximum was reached. After this maximum, increased thermal power resulted in a decrease in conversion efficiency. When lead losses of 12 % were considered, the maximum conversion efficiency was 3.4 %, as indicated by Figure 69.

Ya-21U's output power at higher thermal input power levels was estimated, based on conversion efficiency continuing to increase as thermal input power increased. Figure 70 illustrates the actual output power levels (solid lines) for various thermal inputs. The extrapolated output power levels (dashed lines) indicated Ya-21U would produce ~5.5 kWe for a thermal power input of 120 kW. These estimates corresponded with Russian test results that TOPAZ II systems would produce 5.5 kWe at a reactor power level of 120 kW.

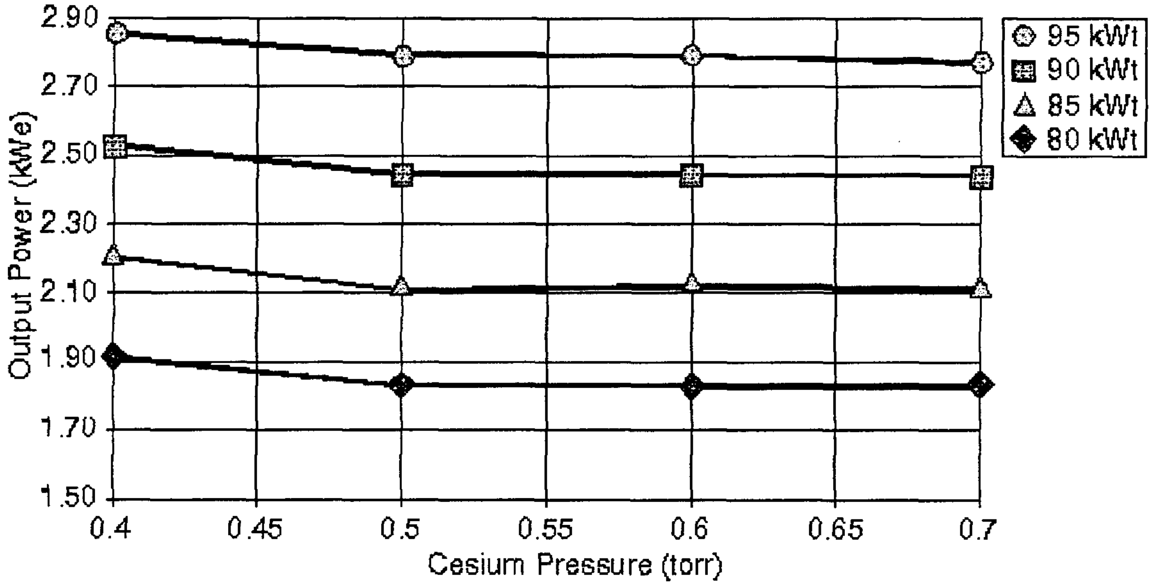


Figure 67. Output power optimization.

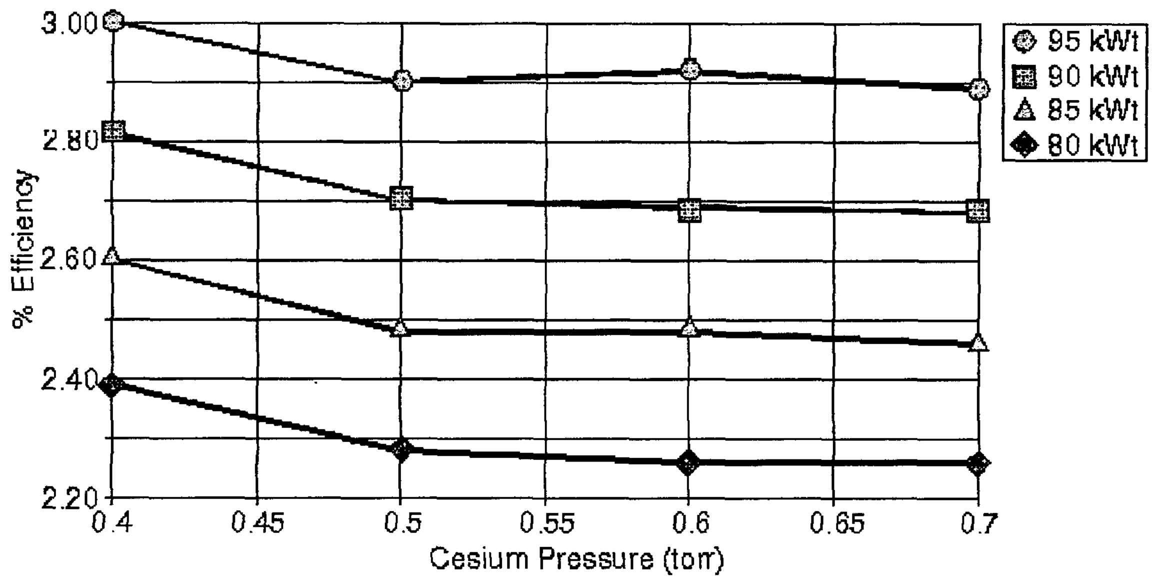


Figure 68. Power conversion efficiency.

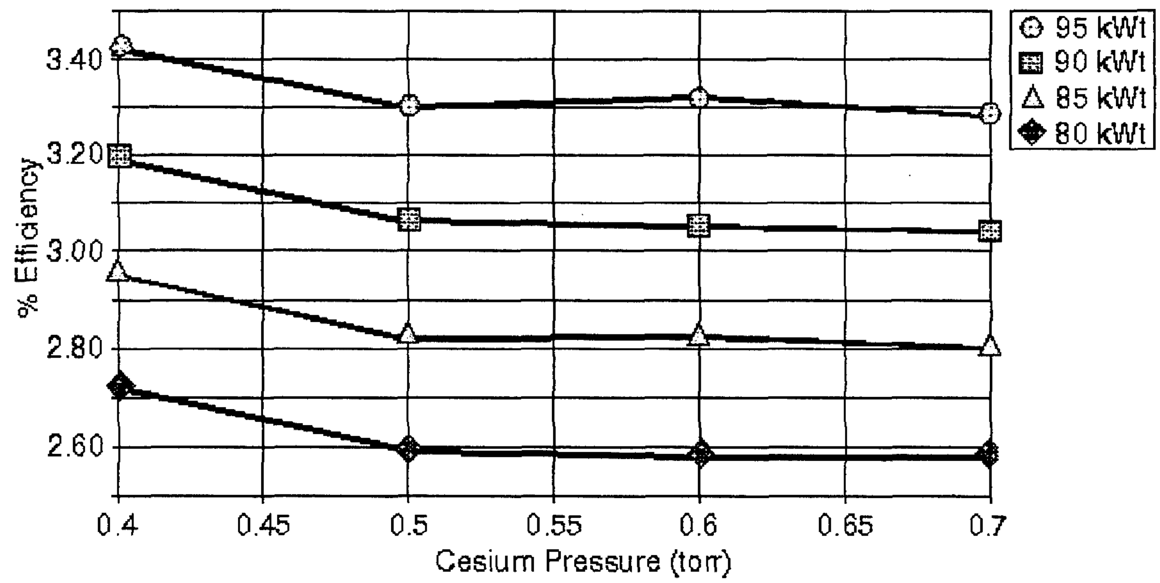


Figure 69. Power conversion efficiency including lead losses.

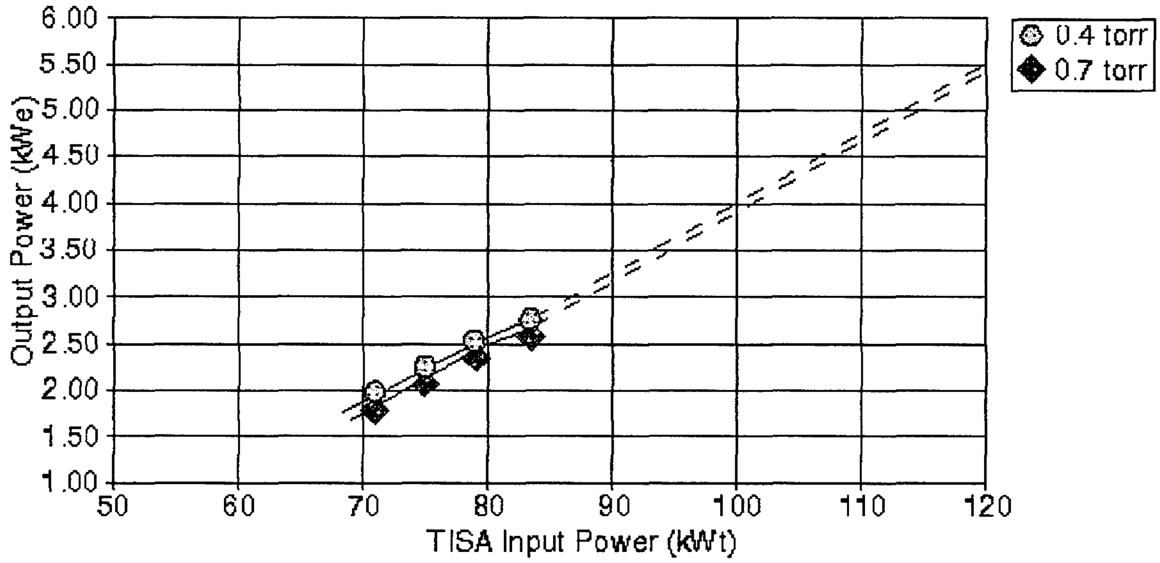


Figure 70. Output power extrapolation.

Ya-21U's work section resistance was calculated as the ratio of output voltage to output current, as indicated by Figure 71. Actual output resistance (solid line) and estimated output resistance (dashed line) were indicated. Estimated work section resistance values corresponded closely to values estimated from the extrapolated output powers indicated in Figure 72. Work section resistances for cesium vapor pressure settings of 0.5, 0.6, and 0.7 torr were nearly identical, while the work section resistance was lower at a cesium vapor pressure setting of 0.4 torr. Within the work section, TFE resistance may have decreased and current increased as the cesium vapor pressure setting was reduced from 0.5 torr to 0.4 torr. An in-depth investigation of this observation was made during follow-on tests of Ya-21U.

Figures 73 through 76 illustrate the relationship between Ya-21U's work section voltage and its power output at cesium vapor pressure settings of 0.4 to 0.7 torr. The data and information were obtained during the 1,000-hr Ya-21U test.

6.5.2 <u>NaK Coolant System Performance</u>

The NaK coolant was heated by waste heat from the Ya-21U work section and EM pump section TFEs as it flowed through the reactor core assembly. After leaving the reactor, the hot coolant flowed down through the LiH radiation shield, where a small amount of heat was lost, and then entered the upper radiator collector and copper-finned radiator tubes, where most of the heat was rejected. From the lower radiator collector, cold NaK coolant flowed up through LiH shield, absorbed heat, and entered the EM pump throats. The EM pump increased the coolant's hydraulic pressure and returned it to the inlet NaK plenum of the reactor and the TFE work section.

During the 1,000-hr test of Ya-21U, the NaK coolant system performed without incident and its integrity was demonstrated during the four thermal cycles, four TISA heater power cycles from 75 to 95 kW, and two rapid cool-downs from 50 and 82 kW. A higher heat transfer capability was evident as TISA heater power and NaK coolant temperatures increased, as indicated by Table 36.

Table 36. Radiator temperature differential.

Power Level kW	Average Inlet Temp K	Average Outlet Temp K	ΔT (Outlet - Inlet) K
75	707	626	-81
80	717	634	-85
85	728	640	-88
90	738	648	-90
95	749	655	-94

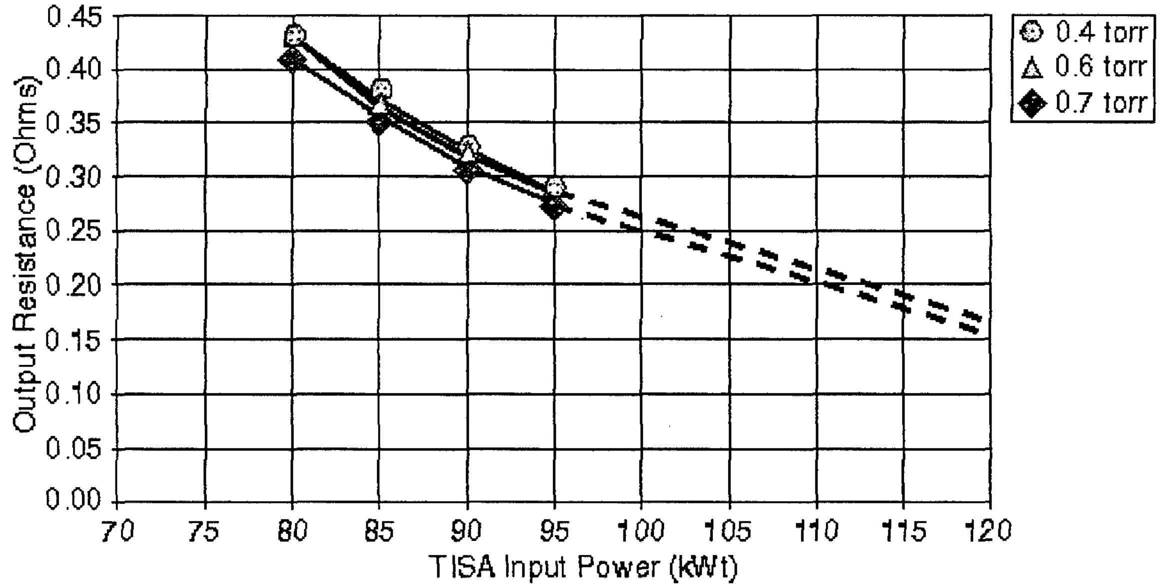


Figure 71. Work section resistance extrapolation.

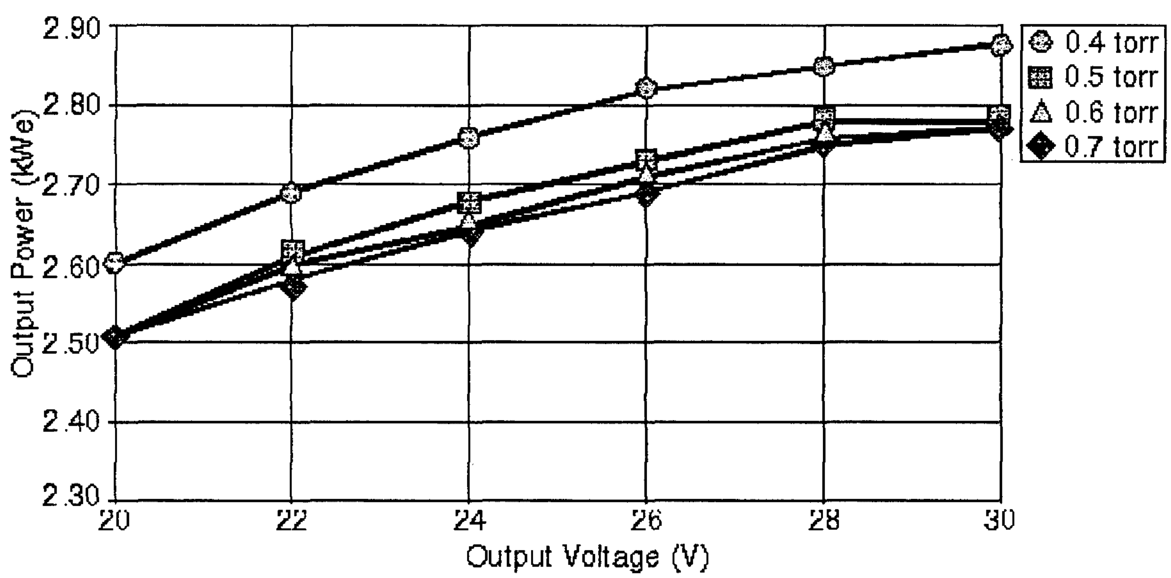


Figure 72. Cesium pressure optimization at 95 kW.

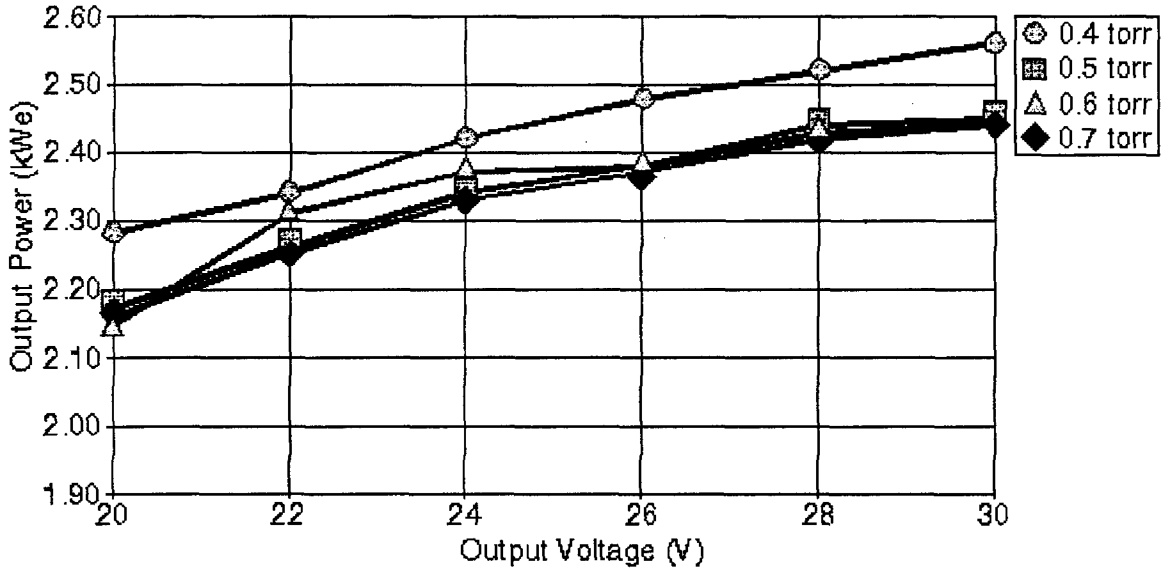


Figure 73. Cesium pressure optimization at 90 kW.

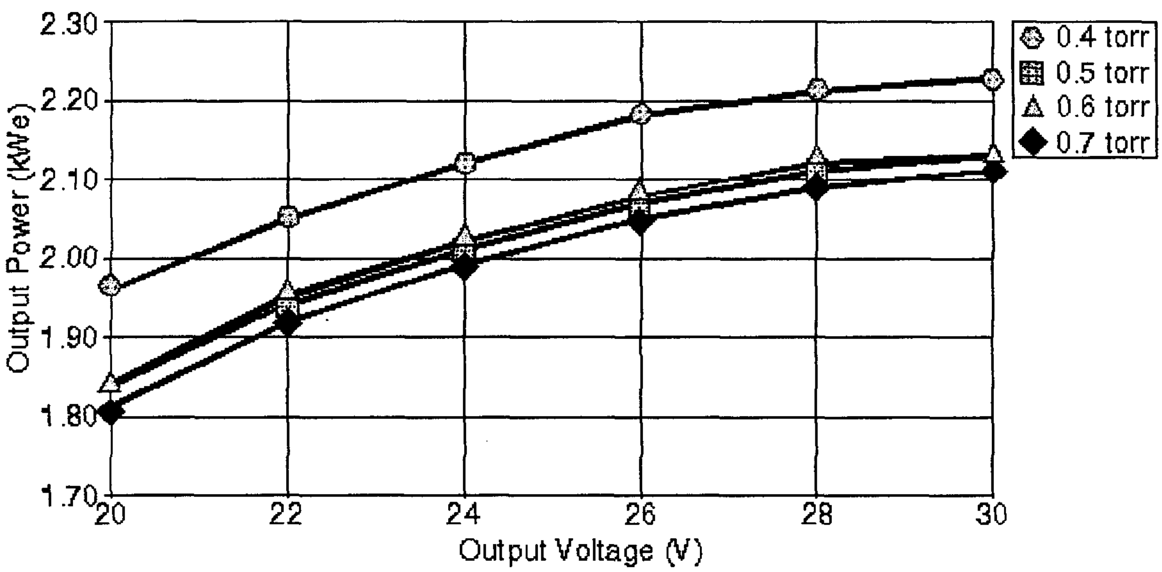


Figure 74. Cesium pressure optimization at 85 kW.

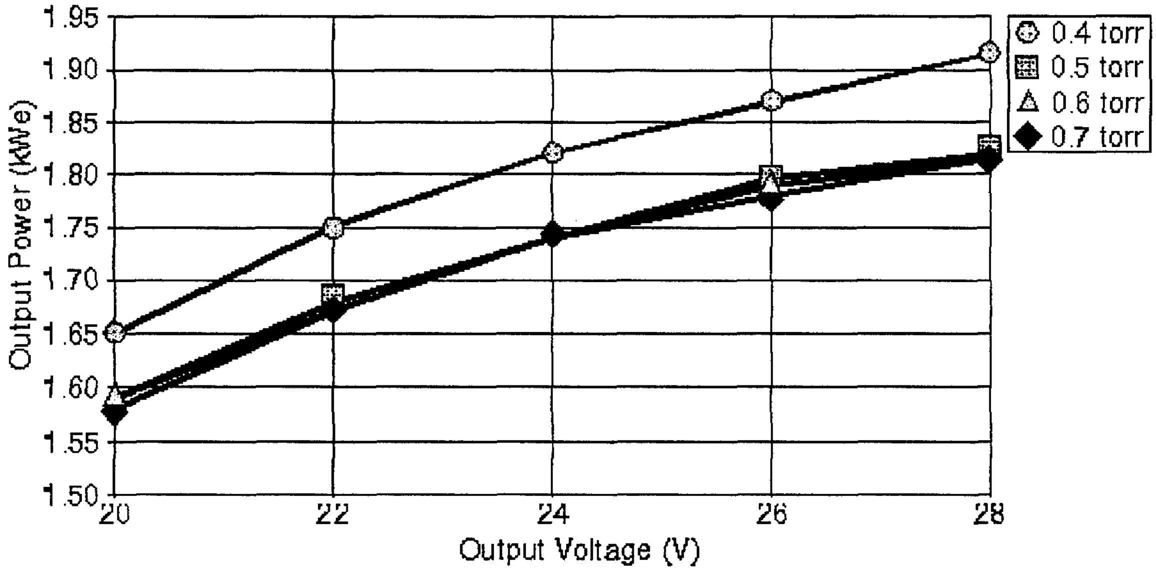


Figure 75. Cesium pressure optimization at 80 kW.

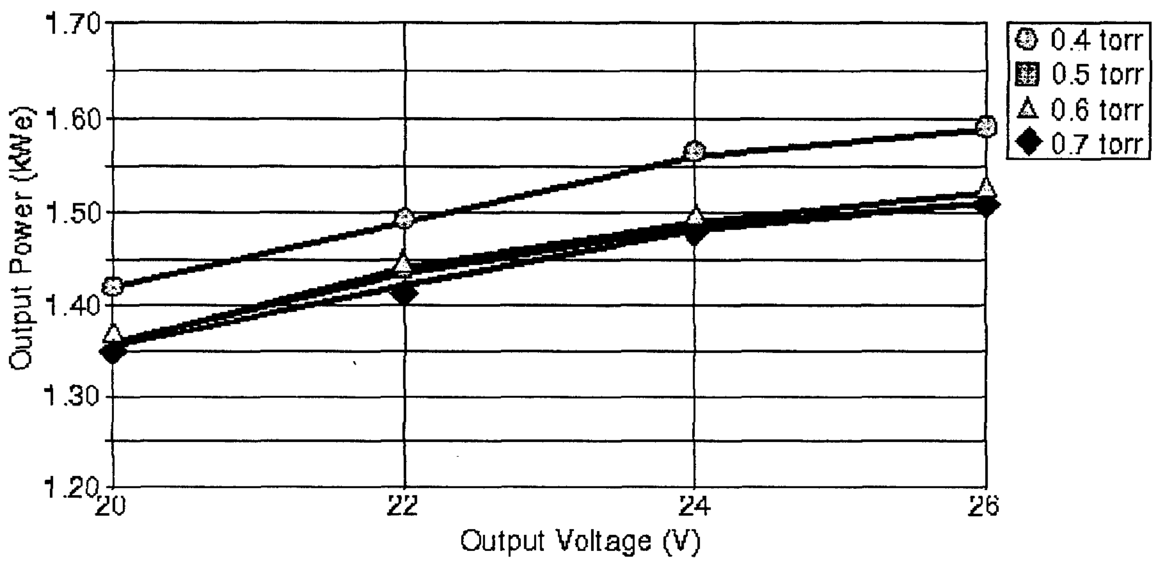


Figure 76. Cesium pressure optimization at 75 kW.

From the Russian summary report of Ya-21U system testing, the NaK coolant temperature was 455°C (728 K) at a TISA heater power level of 85.6 kW and EM pump voltage of 0.32 V, as indicated by Figure 77. During the U.S. 1,000-hr system test at a TISA heater power of 85 kW and EM pump voltage of 0.32 V, the NaK coolant temperature was 481°C (754 K), a difference of +26°C. The higher temperature was caused by the thermal shield installed around the radiator's lower section, which reduced the capacity of radiator to reject heat and raised the temperature of the NaK system, just as it was designed to do for demonstration of the NaK system's integrity. The Russian summary report on Ya-21U performance did not indicate an installation of a thermal shield during system tests.

6.5.3 TFE Performance Comparison

TFEs determined the performance of Ya-21U. Comparison of the volt-amp characteristics of each TFE was an effective method to determine and monitor changes in performance. TFE voltages obtained during Russian tests of Ya-21U were compared with those obtained during the 1,000-hr U.S. test, as indicated by Figure 78.

Most TFE voltages were comparable for a TISA heater power of 85 kW and a cesium vapor pressure setting of 0.6 torr. Significant discrepancies, such as TFE 27, have not been explained. During the 1,000-hr U.S. test, each TFE voltage did not remain constant for each power level, load resistance, and cesium pressure setting. Variations were expected considering the nature of the plasma in the TFE interelectrode gap and that Ya-21U was not operating at the rated thermal input power of 120 kW. Volt-amp characteristics versus constant working section voltage are indicated in Figure 79 for the range of TISA heater power levels during theYa-21U 1,000-hr test.

6.5.4 TFE Leak Evaluations

On October 19 and 20, 1993, post-test inspections and pressure tests were performed and leaks in the cesium system were indicated, as described in Section 4.4.4. After determination of the leak rate and source of the leaks, a joint decision was made by Russian and U.S. specialists to perform another thermal vacuum test on Ya-21U. Test operations resumed on November 29, 1993, and were terminated by failure of the motor-generator reduction gears, which caused a rapid cool-down of Ya-21U. Test operations resumed on December 11, 1993. On December 12, 1993, a work section voltage symmetry shift was observed, remained for 4 days, and then returned to normal. Power optimization tests were repeated to determine the effects of TFE leaks on Ya-21U performance.

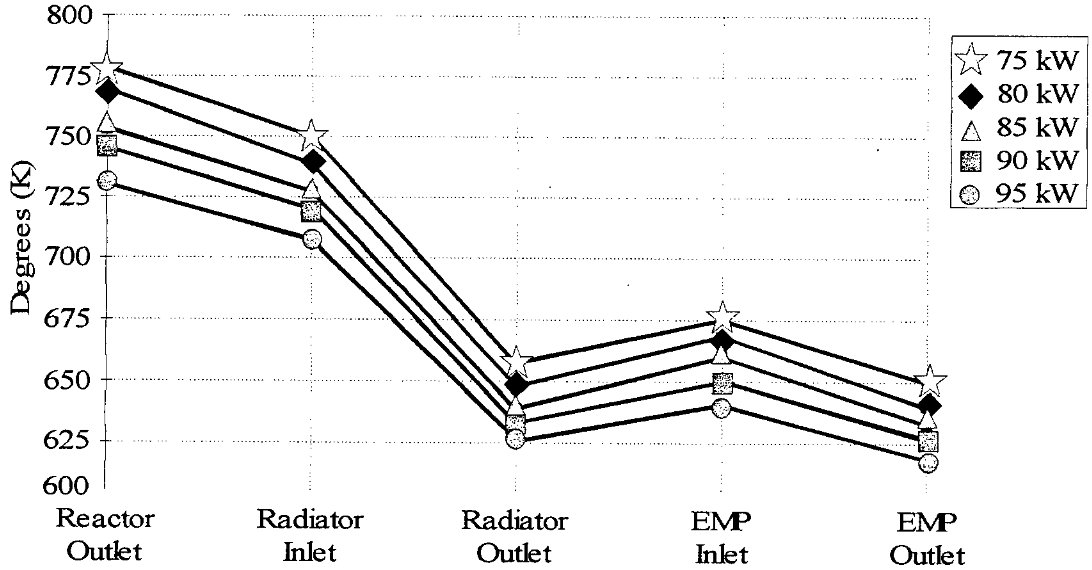


Figure 77. Coolant loop temperature profile.

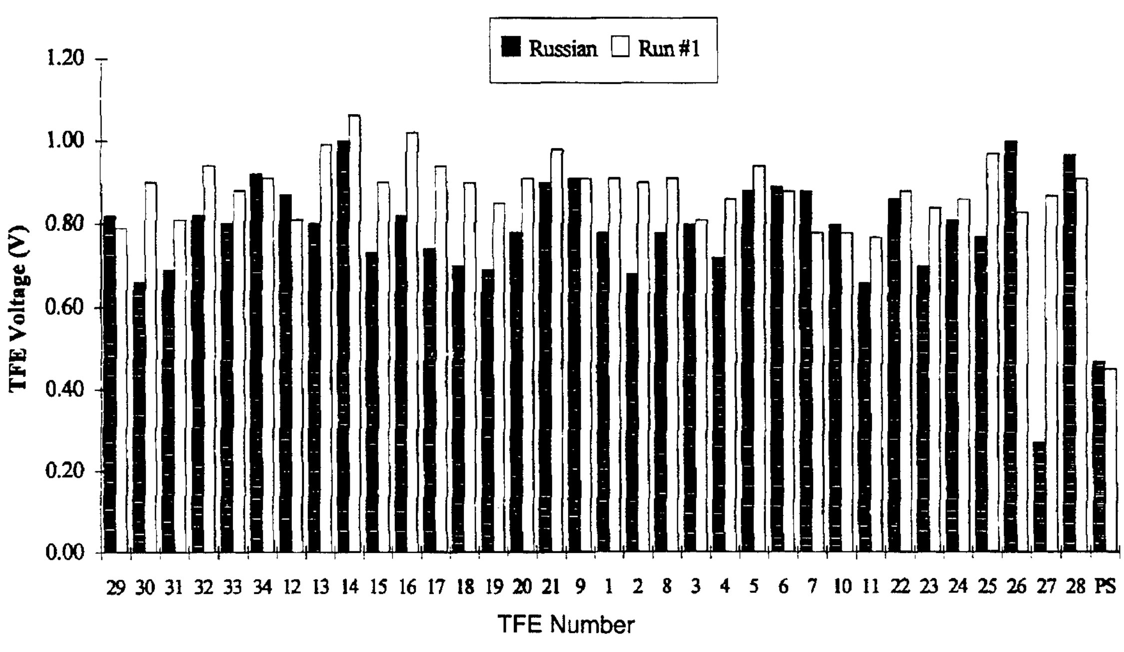


Figure 78. Russian-American TFE potential comparison

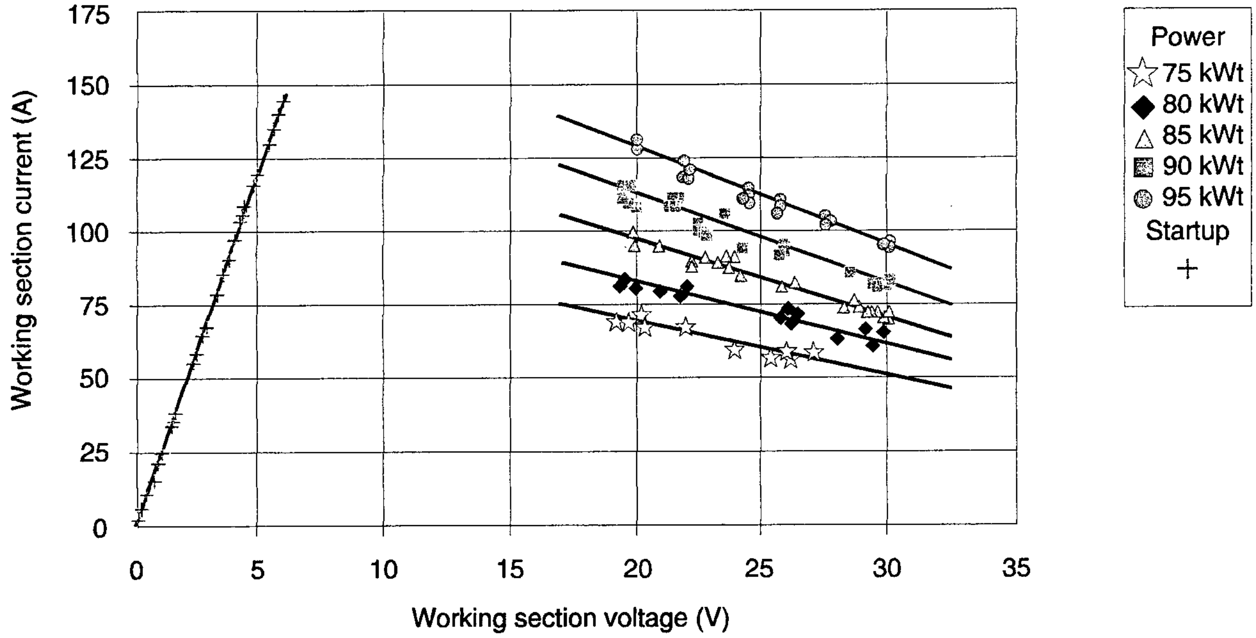


Figure 79. Working section current versus voltage.

On March 7, 1994, system test operations were resumed without the thermal shield. When the TFEs began producing power, a shift in voltage symmetry re-occurred. The system test was terminated, and the short circuit was determined to be caused by a small metal flake lodged between the collector circuit of TFE #26 and the reactor assembly. System tests were resumed on March 12, 1994, and terminated on March 13 by automatic rapid shutdown of the TISA heaters at 85 kW. Inspections indicated TFE leak rates were unchanged and two TISA heaters were damaged. System tests were resumed on April 11, 1994, and were completed successfully on April 15.

During the 4.5-month period from November 29, 1993 to April 17, 1994, Ya-21U received five thermal cycles from TISA power levels above 50 kW to ambient. Two of the five thermal cycles were rapid shutdowns due to unpredictable facility system failures and could have degraded performance of the thermionic converter work section and pump section. In addition, the effects of the TFE leaks could have degraded TFE performance. An analysis of Ya-21U TFEs' optimum performance versus cesium vapor pressure settings was conducted for the 9-month period and provided the following information.

An overview of the performance of a single TOPAZ II TFE (#024) is illustrated by Figure 80. Figure 81 indicates the results of five different power optimization tests of Ya-21U performed during the 9-month period from December 18, 1993 to April 17, 1994. The results of tests in April 1994 were clearly below previous test results. Also, the optimum cesium pressure setting had been 0.4 torr but was 0.7 torr in April 1994. This shift could have been caused by removal

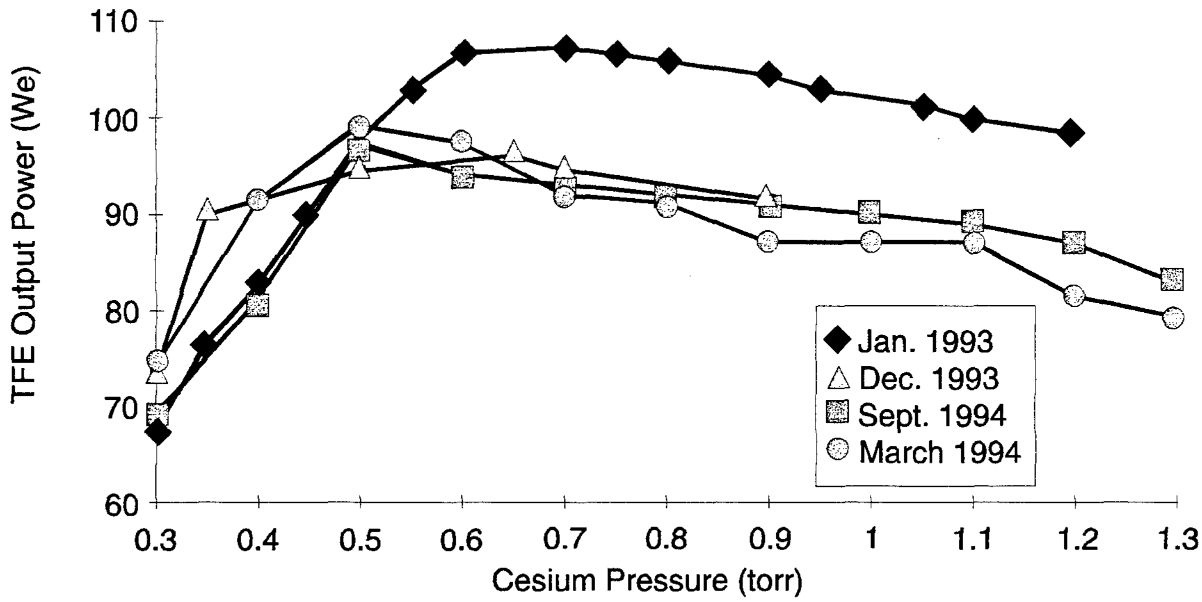


Figure 80. Optimum power output of TOPAZ-II TFE #24.

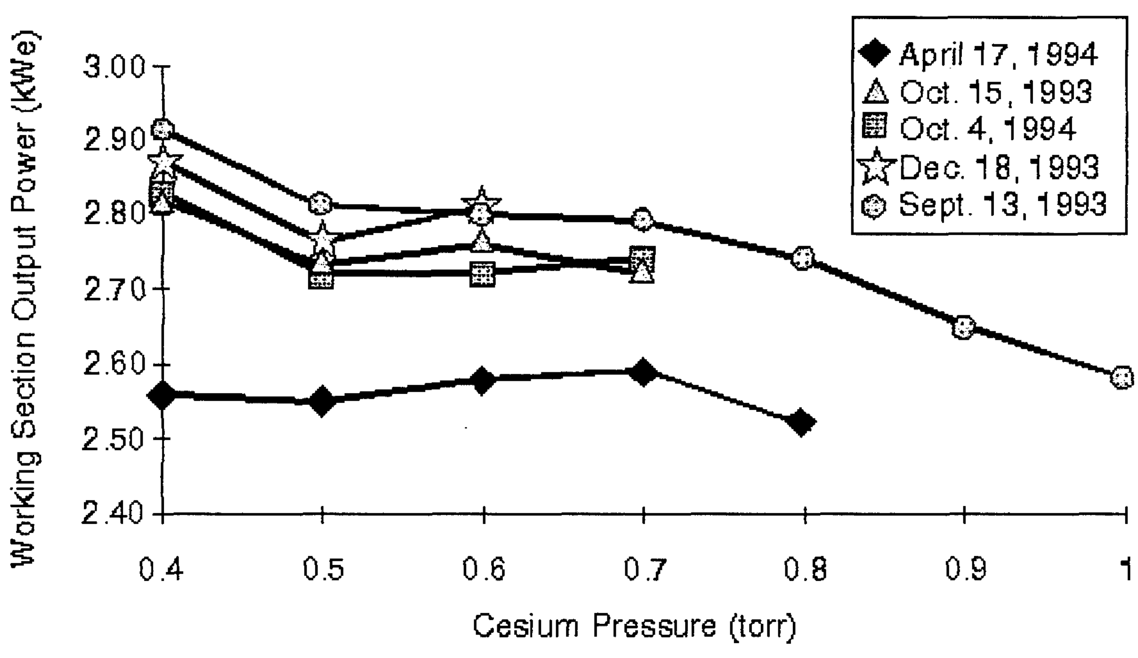


Figure 81. Optimum power output of Ya-21U TFE work section.

of the thermal shield surrounding the lower section of the radiator. Removal of the thermal shield lowered the average TFE collector temperature by ~50°C (50K) during the April 1994 Ya-21U tests, when compared with previous system tests with the thermal shield installed. The lower collector temperature lowered the collector work function, increased the amount of heat energy transferred from the emitter, lowered the emitter temperature, decreased the emitter work function, caused a subsequent decrease in output power of the Ya-21U work section TFEs, and the optimum cesium pressure increased. (Luchau #34, Paramonov #35)

TFE work section output power data versus TISA heater input power data from previous Russian tests of Ya-21U were compared with U.S. test data, as indicated by Figure 82. The comparison indicated that a significant decrease in the Ya-21U TFE work section output power had occurred since its last test in Russia. Figure 83 provides an overview of Ya-21U TFE work section performance since the first test began in May 1993 and was concluded in April 19, 1994.

On two occasions, air was admitted inadvertently into the TFE interelectrode gap because of a leak in insulators of two TFEs. The precise origin of the first leak was unidentifiable. The leak was not present after Russian high power testing of Ya-21U was completed in April 1990. The in-leak was first identified after completion of the Ya-21U demonstration tests in October 1993. A decrease in TFE work section output power from 2.98 to 2.89 kWe occurred sometime between 200 hr and 700 hr of operation at NaK coolant outlet above 500°C (773 K). The second in-leak occurred after shutdown from the 1,000-hr system test in March 1994.

During the 1,000-hr system test, TFE work section output power started at 2.98 kWe and decreased to 2.83 kWe, a difference of 0.15 kWe. The change in power was attributed to oxygen leakage into the interelectrode gaps. The large decrease in work section output power in April 1994 could have been caused by the combined in-leakage of oxygen and thermal shield removal, as previously described.

Detailed calculations and additional Ya-21U system and TFE component tests were required to support and verify the results of the previous system tests.

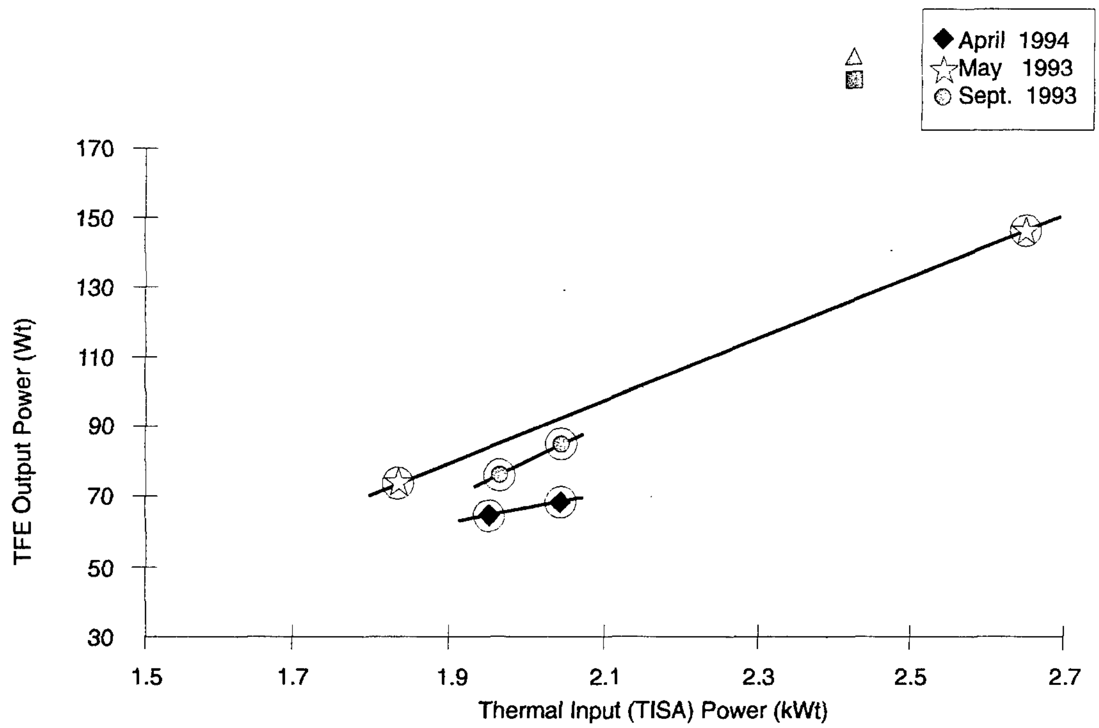


Figure 82. Comparison of Russian and U.S. Ya-21U system power output.

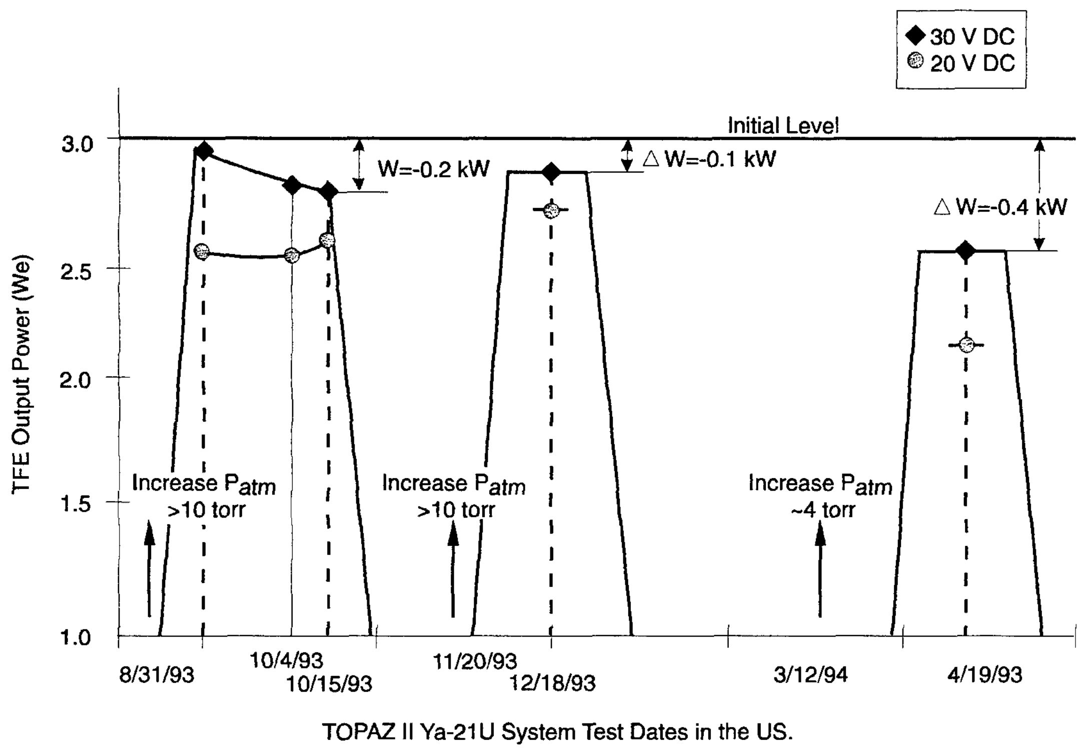


Figure 83. Overview of Ya-21U TFE work section performance.

6.6 COMPARISON OF U.S. AND RUSSIAN MECHANICAL TEST RESULTS

Direct comparison of U.S. and Russian mechanical test results of Ya-21U were not possible because Ya-21U did not undergo such tests in Russia. Therefore, comparisons of test results were made between Russian systems which were tested in Russia and the U.S. tests of Ya-21U.

Four Russian TOPAZ-II systems underwent dynamic mechanical testing from 1972 to 1988, as indicated by Table 37. Two systems were tested in the upright orientation at the beginning of the Russian TOPAZ-II system development with the reactor above the radiator and two were tested in the inverted orientation near the end of system development with the reactor below the radiator. The different orientations were related to planned launch systems, number of systems combined with each launch (possibly three), space applications, and mission profiles which are beyond the scope of this test evaluation report.

Although the Ya-21U system was designed for an inverted Russian launch, it was tested upright at the SNL mechanical test laboratory with its coolant loop filled with NaK. Therefore comparisons were made only with the dynamic tests results of V-13 and V-16. Also, it must be considered that V-13 and V-16 had radiation shields with a mass of 190 kg, whereas Ya-21U had a much heavier radiation shield with a mass of 390 kg. The additional mass of the radiation shield, located some distance above the structural interface between the test fixture and Ya-21U produced additional stresses than would be experienced if tested in the inverted orientation as it was designed to be launched.

Table 37. Russian mechanical tests of TOPAZ-II systems.

System	Dates	Test Orientation	Comments
V-13	1972 - 1973	Upright	Coolant loop filled with water & 56% alcohol
V-16	1975 - 1979	Upright	
V-71	1981 - 1987	Inverted	
Eh-41	1988	Inverted	Coolant loop filled with pure alcohol, mass mockups of several components, heavier shield unit

An broad view of Russian vibration input during the mechanical testing of V-13 and V-16 compared to the planned U.S. mechanical tests of Ya-21U is illustrated by Figure 84.

6.6.1 Major Components Installed on TOPAZ-II Dynamically Tested Systems

Other similarities and variances between U.S. and Russian dynamically tested systems are indicated by the Russian design document number that describes each major component installed on each system. As indicated by Table 38, the frame is the only component that is common to all systems and the volume accumulator, AC drive, safety drive, and IC suspensions are common between V-16 and Ya-21U systems.

It is also important to note that both units V-13 and V-16 were tested with the inverted thermal cover installed, whereas Ya-21U did not have a thermal cover installed during the dynamic tests.

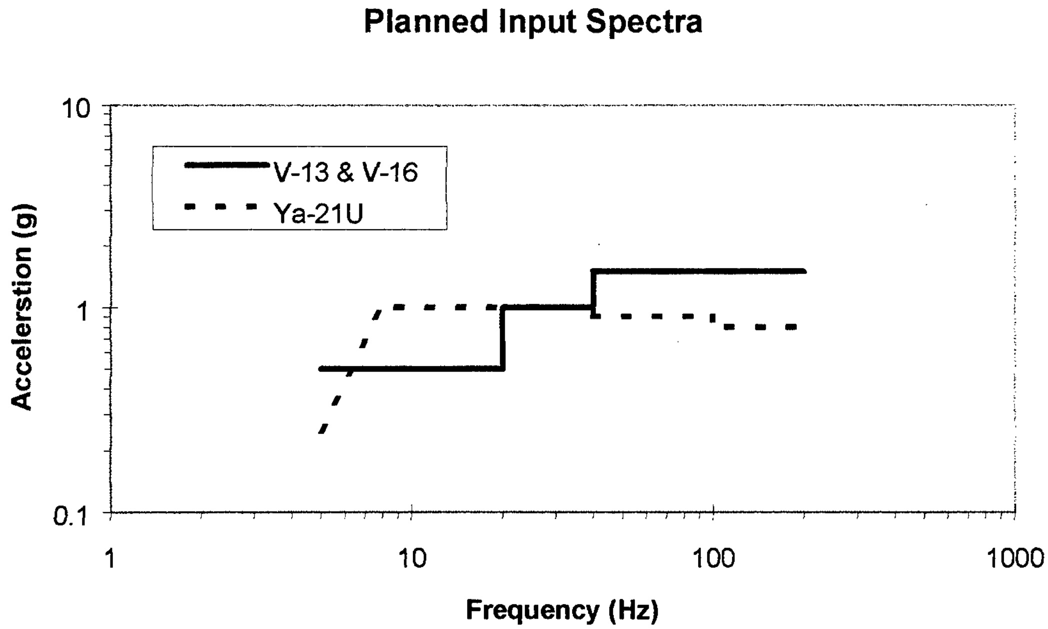


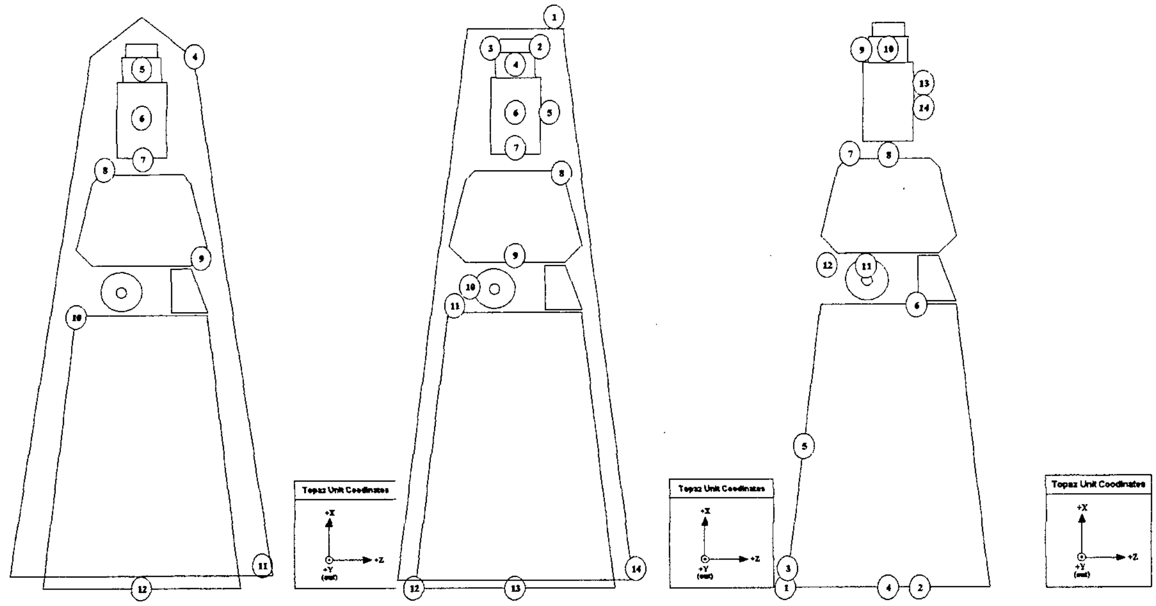
Figure 84. Russian vibration tests of V-13 and V-16 systems compared with U.S. tests of Ya-21U.

Table 38. Major components on TOPAZ-II dynamically tested systems.

Major Components	V-13	V-16	Ya-21U
Reactor	182-07-0023	182-07-0030	182-07-0040-01
Reactor Fuel	Mass mock-up	Mass mock-up	Mass mock-up
Radiation Shield	192-08-0010	182-08-0015	182-08-0016
Frame	182-20-0007	182-20-0007	182-20-0007
Radiator	182-29-0020	Not Identified	182-29-0022
Volume Accumulator	182-30-0015	182-30-0026	182-30-0026
Thermal Cover	182-39-0008	182-39-0008	Not Installed
AC Drive	182-46-0010	182-46-0011	182-46-0011
Safety Drum Drive	182-47-0003	182-47-0005	182-47-0005
IC Suspensions	182-51-0005	182-51-0007	182-51-0007
Startup Unit	182-67-0004	182-67-0011	1515-34-0100 (mock-up)
Pressure Gage Unit	182-69-0005	182-69-0012	182-69-0015
Cesium Unit	Not Identified	182-28-0026	182-28-0026-01
Electric Cable Bundle	Not Identified	182-68-0015	182-68-0021

6.6.2 Location of Accelerometer Sensors on the Dynamically Tested Systems

The relative locations of accelerometers used during dynamic tests of V-13, V-16, and Ya-21U are indicated by Figures 85a, 85b, and 85c. Table 39 indicates the specific location of each accelerometer and Table 40 identifies the sensor number based on similar locations.



(a.) V-13 (b.)V-16 (c.) Ya-21U

Figure 85. Accelerometer locations on V-13, V-16, and Ya-21U systems.

Table 39. Locations of accelerometers on V-13, V-16, and Ya-21U systems

Sensor No.	V-13	V-16	Ya-21U
1	Not indicated	Top of thermal cover	Base of frame (-Z)
2	Not indicated	Top of reactor (+Z)	Base of frame (+Y)
3	Not indicated	Top of reactor (-Z)	Bottom radiator collector (-Z)
4	Top of thermal cover	Upper plenum of reactor	Bottom radiator collector (+Y)
5	Top of reactor	Side of reactor (+Z)	Mid-joint on frame
6	Side of reactor	Side of reactor (+Y)	Upper frame joint (+Y)
7	Reactor leg bracket	Reactor leg bracket	Reactor leg bracket (-Z)
8	Top of shield unit	Top of shield unit	Reactor leg bracket (+Y)
9	Bottom of shield unit	Bottom of shield unit	Upper plenum of reactor (-Z)
10	Upper cross piece of frame	Umbilical connector	Upper plenum of reactor (+Y)
11	Bottom of thermal cover	Upper frame joint (-Z)	Side of cesium unit
12	Base of frame	Base of frame (-Z)	Startup unit mockup
13	Not indicated	Base of frame (+Y)	Not installed
14	Not indicated	Bottom of thermal cover	Not installed

Table 40. Comparison of accelerometer locations on V-13, V-16, and Ya-21U systems

Sensor Locations	V-13	V-16	Ya-21U (lateral tests)	Ya-21U (vertical tests)
Top of thermal cover	4 (x, y, z)	1 (x, y, z)	Not installed	Not installed
Top of reactor	5 (x, y, z)	2 (x), 3 (x)	Not installed	Not installed
Upper plenum of reactor	Not installed	4 (x, y, z)	9 (x, y, z)	9 (x, z), 10 (x, z)
Side of reactor	6 (x, y, z)	5 (y, z), 6 (x, y, z)	Not installed	Not installed
Reactor leg bracket	7 (x, y, z)	7 (x, y, z)	7 (z), 8 (z)	7 (x), 8 (x)
Top of shield unit	8 (x, y, z)	8 (x, y, z)	Not installed	Not installed
Bottom of shield unit	9 (x, y, z)	9 (x, y, z)	Not installed	Not installed
Umbilical connector	Not installed	10 (y)	Not installed	Not installed
Side of cesium unit	Not installed	Not installed	11 (x, y, z)	11 (x, y, z)
Startup unit	Not installed	Not installed	12 (x, y, z)	12 (x, y, z)
Upper frame joint	10 (x, y, z)	11 (x, y, z)	6 (x, z)	6 (x, z)
Mid-joint of frame	Not installed	Not installed	5 (x, z)	5 (x)
Base of frame	12 (x, y, z)	12 (x, y, z), 13 (x, y, z)	1 (x, y, z), 2 (y, z)	1 (x, y, z), 2 (x, y)
Lower radiator collector	Not installed	Not installed	3 (z), 4 (y)	3 (x), 4 (x)
Bottom of thermal cover	11 (x, y, z)	14 (x, y, z)	Not installed	Not installed

6.6.3 Russian Sine Vibration Tests

Sine vibration tests were performed to determine resonant frequencies and to determine overloads at all frequencies which correspond to the conditions that the system would experience during launch into orbit.

During the dynamic tests, vibration forces were provided by an electrodynamic test stand with an excitation frequency from 5 Hz to 2,500 Hz. Adapters between the test stand and TOPAZ-II systems were designed with natural frequency greater than 200 Hz. The systems were suspended by elastic cables to unload the electrodynamic test stand shaker when vertical axis tests were performed.

The sine vibration tests to determine resonant frequencies were performed in each of three mutually perpendicular axes, as indicated by Table 41. Frequency sweeps were performed using a smooth change of sinusoidal vibration frequency in the range from 5 Hz to 200 Hz with minimum input g-loadings sufficient to determine structural damping forces.

Table 41. Resonant frequency test conditions for V-13 and V-16 systems.

Frequency-Hz	Acceleration-g	SweepTime-sec
5 - 20	0.5	190
20 - 40	1.0	100
40 - 200	1.5	195

After completion of the resonance frequency tests, sine vibration tests were performed in each of three mutually perpendicular axes with a duration of ~30 min in each direction at the frequency and load range, as indicated by Table 42.

Table 42. Sine vibration test conditions for V-13 and V-16 systems.

Frequency-Hz	5 - 50	50 - 600	600 - 2000	2000 - 2500
Acceleration-g	1 - 3	3 - 10	10 - 12	5

The sine vibration tests were performed at the modes indicated in Table 43 for specific frequencies of 5, 7, 10 Hz and for the range of 10 - 2,500 Hz. The frequency range was swept from the lower frequency to the higher frequency and then back to the lower frequency. Time durations provided in Table 43 are for the durations in one direction. The acceleration levels were monitored at the interface between the test system adapter and shaker.

Technological vibration tests were also conducted at ~23.8 Hz along the X-X axis for 30 min with an applied acceleration force of 2 g. Significant resonance of components were not observed during the sweep from 20 Hz to 25 Hz.

Table 43. Vibration test durations for V-13 and V-16 systems.

Frequency, Hz	Acceleration, g	Duration, sec
5	1.1	14
7	1.2	14
10	1.3	14
10-20	1.6	120
20-40	2.2	120
40-50	2.8	120
50-80	3.2	120
80-160	3.9	120
160-320	5.4	120
320-640	8.3	120
640-1280	10.6	120
1280-2000	11.5	70
2000-2500	5.0	225

6.6.4 Russian Shock Test Input

During shock tests, the Russian systems were subjected to three single shocks in each of the three mutually perpendicular axes (X-X, Y-Y and Z-Z) with a shock force of 40 g for a 2-6 msec pulse duration, as indicated by Table 44.

Table 44. Shock test conditions for Russian V-13 and V-16 system tests.

Direction	Number of shocks	Duration, msec	Acceleration, g
X-X	3	4.5	40
Y-Y	3	4.0	40
Z-Z	3	4.0	40

The acceleration levels were monitored at the interface between the test system adapter and shaker platform.

6.6.5 Comparison of Russian and U.S. Dynamic Sine Vibration Test Results

Peak amplification factors and frequencies observed during the Russian and U.S. lateral and vertical sine vibration system tests are indicated by Table 45.

Table 45. Comparison of Russian and U.S. peak amplification factors

Accelerometer Location	V-13	V-16	Ya-21U
Lateral Sine Tests:			
Top of reactor/plenum	2.51 @ 30 Hz	3.2 @ 28 Hz	26 @ 8.6 Hz
Reactor leg bracket	1.12 @ 55 Hz	1.7 @ 51 Hz	17.7 @ 8.6 Hz
Upper frame joint	2.24 @ 30 Hz	1.12 @ 26 Hz	8.33 @ 8.6 Hz
Base of frame (-Z)	Not installed	1.2 @ 120 Hz	2.1 @ 9 Hz
Base of frame (+Y)	The input control sensor	2.1 @ 190 Hz	1.8 @ 8.7 Hz
Vertical Sine Tests:			
Top of reactor/plenum	2.0 @ 60 Hz	1.7 @ 47 Hz	4.85 @ 39 Hz
Reactor leg bracket	1.41 @ 70 Hz	1.2 @ 43 Hz	3.5 @ 39 Hz
Upper frame joint	1.5 @ 57 Hz	3.3 @ 159 Hz	5 @ 39 Hz
Base of frame (-Z)	Not installed	1.3 @ 185 Hz	2.5 @ 38 Hz
Base of frame (+Y)	The input control sensor	2.7 @ 183 Hz	1.8 @ 37.5 Hz

6.6.6 Post-Test System Integrity Check Results

Post-test inspections and checks of the Russian V-16 system indicated that the main structure, coolant loop, gas cavities and piping were not damaged during the tests. However, some loosening of thread connections and reduction of circuit isolation resistance from the vessel and between unconnected circuits were detected. These observation were confirmed during subsequent thermal vacuum tests,

Post test inspections and checks on Ya-21U following the U.S. mechanical tests resulted in the findings listed below.

- A nut fell off of a clamp on lower collector.
- Bolts that attached the startup unit mass mockup were loose.
- Other loose bolts were noted and tightened.

During re-installation of Ya-21U in the Baikal test stand vacuum chamber, leaks in the cesium unit vapor vent line were detected and determined to be caused by cracks near a seal weld. The leak rates were determined to be ~$7x10^{-6}$ mbar×l/s and $4.5x10^{-5}$ mbar×l/s..

During leak checks of each TFE, leaks were detected in TFEs No. 1, 7, 8, 10, and 20. The leaks were determined to be in the same TFEs that were checked before the system vibration test. Results of the pre- and post-test leak checks are indicated by Table 46.

Table 46. Comparison of Ya-21U TFE leaks before and after mechanical tests.

TFE Identification Number/Location	Checks Before on 08/22/94, l/s	Checks After on 10/06/94, l/s
1	$2.9x10^{-7}$	$3.9x10^{-7}$
7	$1.3x10^{-10}$	< Min. Detectable
8	$4.6x10^{-8}$	$2.5x10^{-8}$
10	$22.3x10^{-6}$	$3.9x10^{-7}$
20	$6.9x10^{-7}$	$6.8x10^{-8}$

6.6.7 Analysis of Ya-21U Test Results

Performance changes occurred from one test to the next during steady-state operation of Ya-21U over the entire Russian and U.S. test history (Paramonov #35 and Nechaev #36). As indicated by Figure 86, Ya-21U was subjected to 23 thermal cycles above a TISA input power of 50 kW. This operating history includes three distinct testing stages:

1. After fabrication in Russia;
2. Following air incursion during initial tests in the U.S; and
3. After shock and vibration test in the U.S.

Also, Figure 87 indicates Ya-21U's output power for TISA input power levels of 85, 95, and 105 kW at ~28-29 V and cesium pressure setting of 0.6 - 0.7 torr for the entire test period.

6.6.7.1 Analysis of Results of Russian and U.S. Test Results

As indicated by Figure 87, Ya-21U's performance in Russia decreased slowly from 2.85-2.45 kWe to ~2.2 kWe at a TISA power of 85 kW, although it was subjected to 8 thermal cycles. According to Russian specialists, the initial high output power of 2.85 kWe was attributed to the beginning non-equilibrium operation of the cesium supply and the initial surface condition of the TFE electrodes. According, this initial output should not be considered as steady-state performance (Sinkevich #37).

Excluding this initial high power level, the output power decreased by ~ 0.13 kWe during the period prior to the start of the high power demonstration at a TISA power input of 123 kW. Thereafter, when TISA power was reduced to 85 kW, Ya-21U output power had decreased by ~0.23 kWe. The additional decrease could have been attributed to several causes; i.e., damage of the spacers within interelectrode gaps of TFEs or to overheating of brazed joints at the top of TFEs that occurred during the high power demonstration test at 123 kW input.

Later, a greater change was observed during initial performance tests of Ya-21U in the U.S than was observed in Russia. During test #1 at an input TISA power of 85kW, power output was observed to be ~2.1 kWe after more than 4,200 hr of testing and decreased to ~1.9 kWe after 5,980 hr. This change in performance could be attributed to a combination of mechanical shocks and vibrations during shipment to the U.S. and/or oxygen contamination of the cesium supply system, which could cause mass transport from the emitters and deposition of tungsten on the interelectrode gap spacers and collectors.

The output power of Ya-21U, at a TISA input power of 95 kW, decreased from ~2.67 kWe prior to vibration and shock tests at the SNL mechanical test facility to ~2.35 kWe during the very next test (test #10), also indicated by Figure 87.

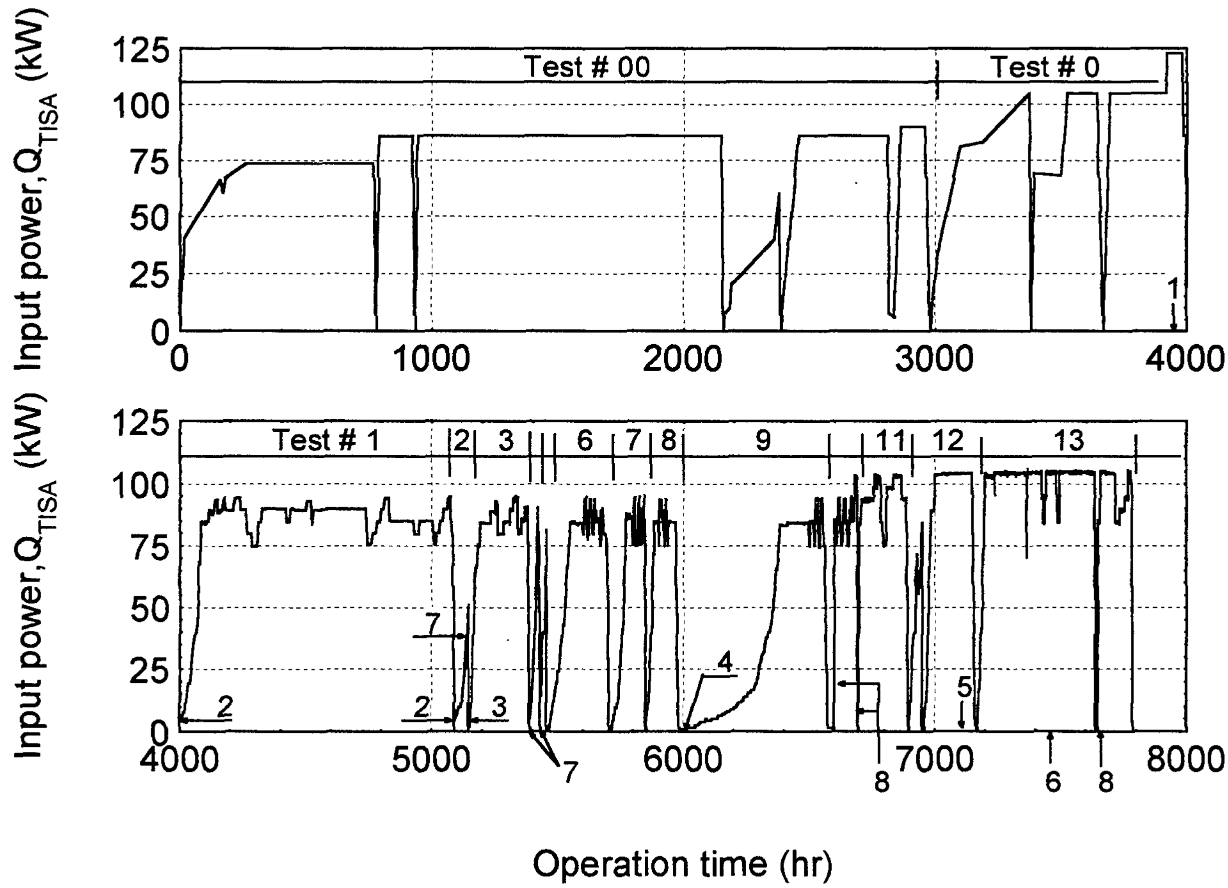


Figure 86. Input power to electric heaters throughout the operation history of Ya-21U.

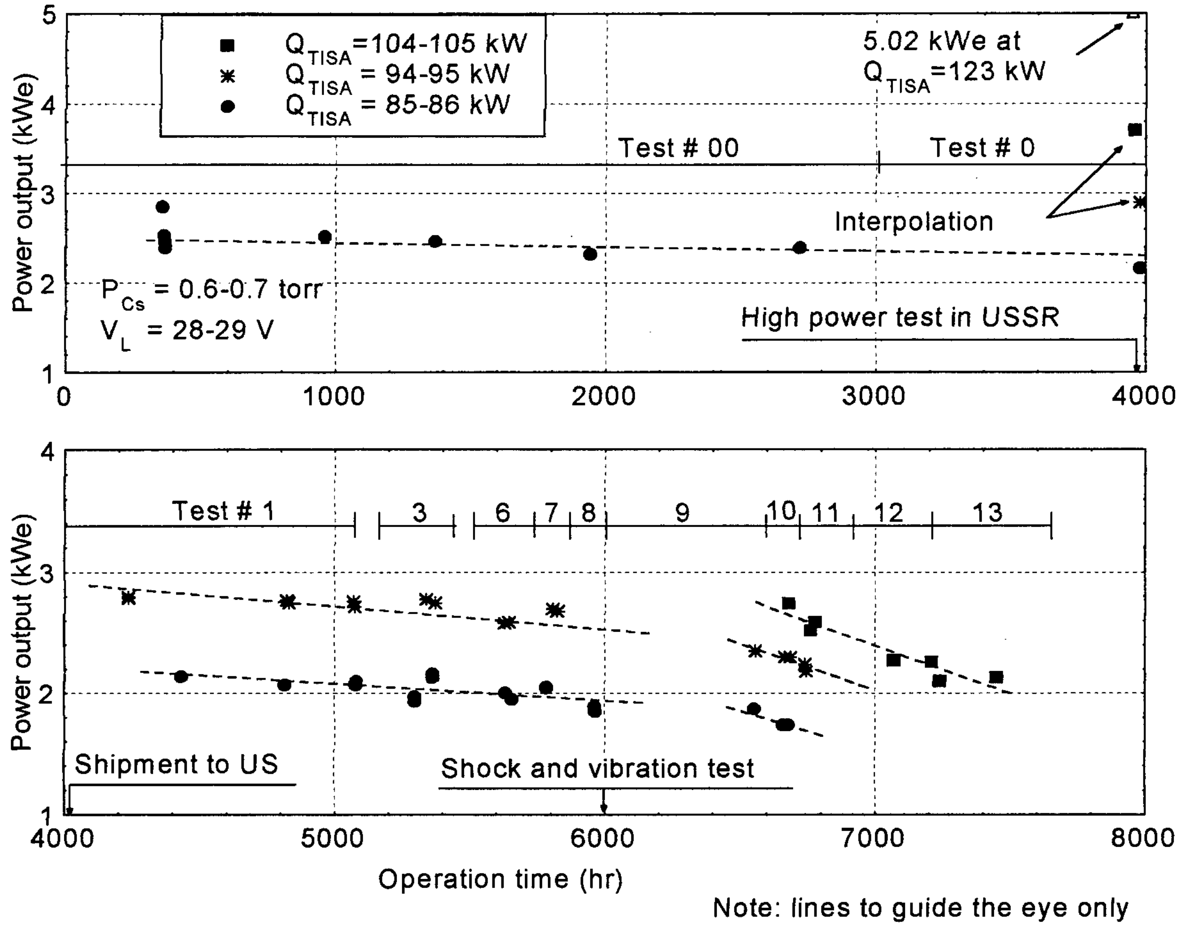


Figure 87. Power output of Ya-21U at different input power levels.

A comparison of the estimated power output of Ya-21U at a TISA power input of 105 kW in Russia (prior to the high-power test) with the U.S. test #10 at the same TISA power indicated a power decrease from 3.6 to 2.75 kWe. The ~800 hr of additional testing during tests #10-#13 resulted in an additional power decrease of ~0.65 kWe when Ya-21U was operated at a TISA input power of 105 kW.

6.6.7.2 Single Effect Evaluations

After vibration and shock tests of Ya-21U, single effect evaluations were made at steady-state test conditions during tests #12 and #13 to assess performance changes related to changes in cesium pressure and resistive loads. As indicated by Figure 88, the slope of the volt-ampere characteristics (at a TISA power input of ~95 kW and 0.6 torr cesium pressure setting) increased significantly while currents at high resistive loads (voltages) decreased in the unignited mode. A similar change is usually observed in thermionic converters when cesium pressure is increased. This observation suggested that the vibration and shock tests could have damaged the cesium

throttle valve, altered the cesium throttle valve pressure calibration curve, and produced a higher than expected cesium vapor pressure.

Other indications of abnormal behavior of the cesium vapor supply system following the vibration and shock tests of Ya-21U are illustrated by Figure 89. The plot of optimum output power from Ya-21U for cesium vapor settings between 0.3 and 1.4 torr at a TISA input power of ~95 kW indicated the following:

- Optimum power continued to increase as the cesium vapor pressure settings decreased to 0.4 torr.

- Optimum power output was not achieved during initial tests #1-#8.
  Note: The optimum power was not achieved because Russian specialists strongly discouraged operation of the Ya-21U work section TFEs at cesium vapor pressure settings below 0.4 torr.

- Only minor changes in output power were observed for the range of cesium pressure settings investigated in tests #1-#8. This emphasizes that the optimum cesium pressure setting was below 0.4 torr.

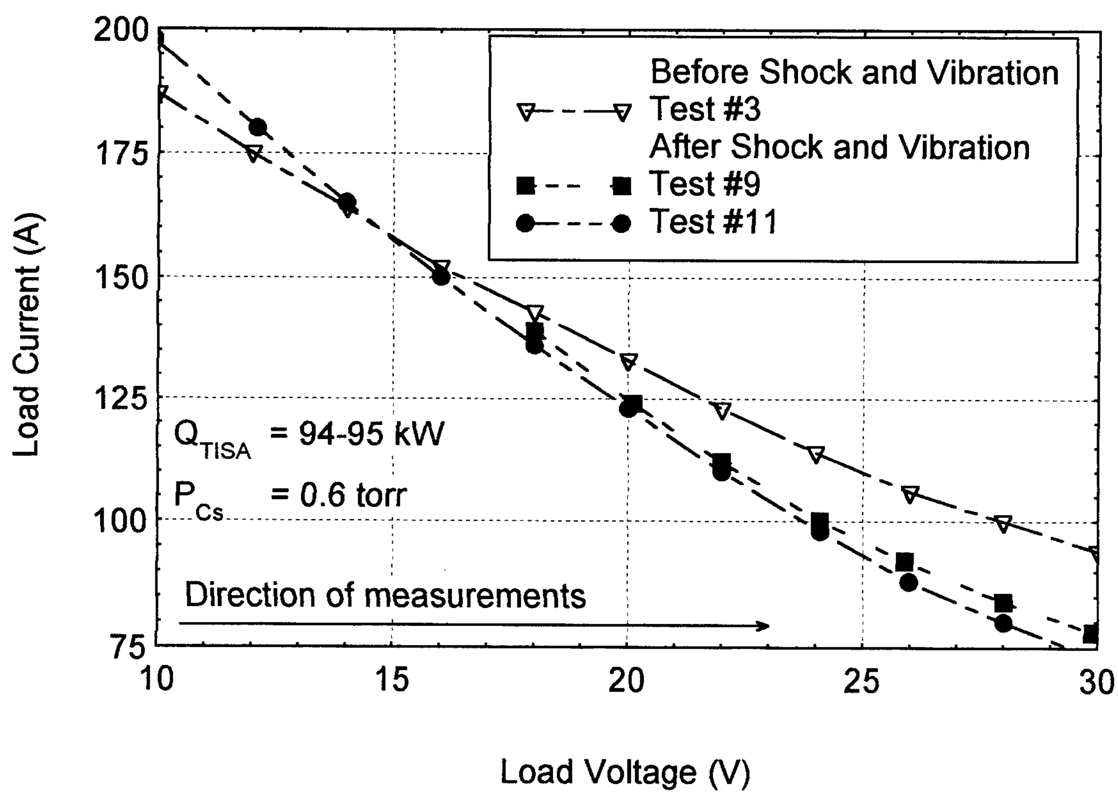


Figure 88. Volt-ampere characteristics of Ya-21U work section at TISA power input of 94 - 95 kW.

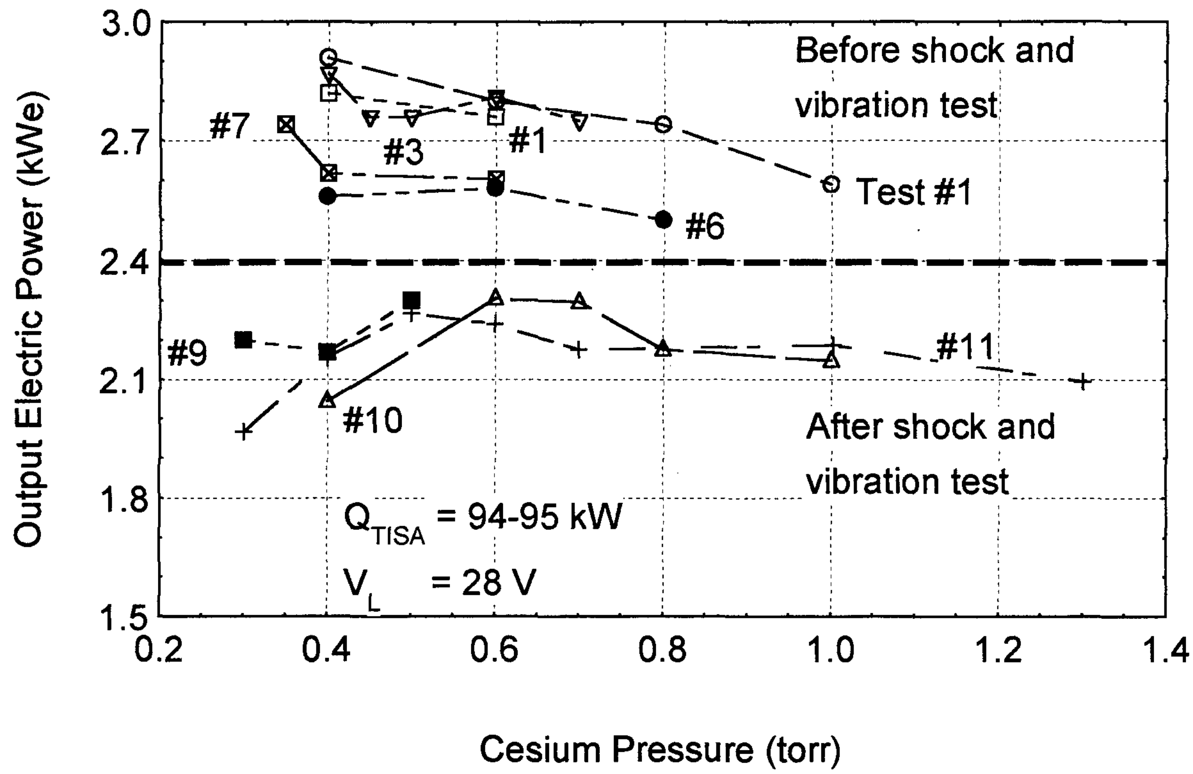


Figure 89. Ya-21U output power optimization with respect to cesium pressure.

- Vibration and shock tests caused the optimum cesium pressure setting at a TISA power input of 95 kW to shift from below 0.4 torr to 0.6-0.7 torr, as indicated for tests #9-#11. This observation supports the presence of additional cesium vapor leaks from the cesium system and/or TFEs or a change in calibration of the throttle valve. Note: As indicated in previous sections of this report, direct measurement of the cesium vapor pressure in the cesium vapor supply system was not possible because cesium vapor pressure sensors were not included in the design of the TOPAZ-II systems.

6.6.7.3 Comparison of TFE Electrode Emissivity Estimates

The effective emissivity values and the cesiated work functions of the Ya-21U TFEs were estimated and compared with reported Russian information for uncontaminated TOPAZ-II TFEs of the same type. (Paramonov #35)

The estimates were based on Ya-21U work section measurements of the ignited and unignited volt-ampere characteristics. The ignited mode volt-ampere characteristics were obtained during December 1993 at TISA input power levels of 90 and 95 kW and a cesium pressure setting of 0.6 torr. The unignited mode volt-ampere characteristics were obtained in April 1994 at TISA input power input levels of 85, 90, and 95 kW and a cesium pressure setting of 0.6 torr. In addition,

ignited mode characteristics were also obtained in December 1994 at TISA power input levels of 95, 100, and 105 kW and at cesium pressure settings of 0.4, 0.6,1.0 and 2.0 torr.

The estimated values of the effective emissivity of Ya-21U TFE electrodes were compared with values reported by Russian investigators, as indicated by Figure 90 (Nikolaev #38). Current estimated Ya-21U TFE electrode emissitvity values and those reported by Nikolaev in 1991 and 1992 were obtained for the 300 mm long heat transfer region between the Ya-21U type TFE emitter and collector. This comparison revealed the following:

- The average effective emisivity of Ya-21U TFEs was 0.03 - 0.035 higher than that for the uncontaminated Russian TFEs. This variance indicated that impurities in the interelectrode gaps of Ya-21U TFEs had significantly changed their surface condition and properties of the electrodes.

- The emitter temperatures of the Ya-2U TFEs were significantly lower than predicted by the TITAM computer model that used the effective emissivity for uncontaminated TFE reported by Russian investigators.

- The estimated effective emissitivity of the Ya-21U TFEs varied within a narrow range of +/-0.002.

- The estimated effective emissivity of the Ya-21U TFEs was lower than that for thermionic converters, which were assembled in air without use of special procedures for cleaning their electrodes (~0.2 - 0.2 - not indicated by Figure 90).

The above comparisons indicated the incursion of air into the Ya-21U TFEs increased the effective emissivity of the TFE electrodes, lowered the emitter temperatures, and was partially responsible for performance change of Ya-21U.

6.6.7.4 Transitions from Diffusion to Ignited Modes

Increasing the cesium pressure in TFEs causes a transition from the diffusion to the ignited mode of operation to occur within the interelectrode gaps of the TFEs (Hatsopoulos and Gyftopoulos #39). Increasing the cesium pressure also changes the optimum load voltage which is lower in the ignited mode than in the unignited mode. Accordingly, it was necessary to compare the output of Ya-21U's TFEs at the optimum cesium pressure and load voltage in order to quantify changes in Ya-21U's performance. This comparison was made at a TISA input power of 95 kW, as indicated by Figure 91.

During tests #1-#8, the measured optimum load voltage was almost the same as the nominal load voltage of 28-30 V. However, after vibration and shock tests, the TFEs' operation shifted toward the ignited mode at the same cesium pressure setting while the optimum load voltage decreased to 18 V.

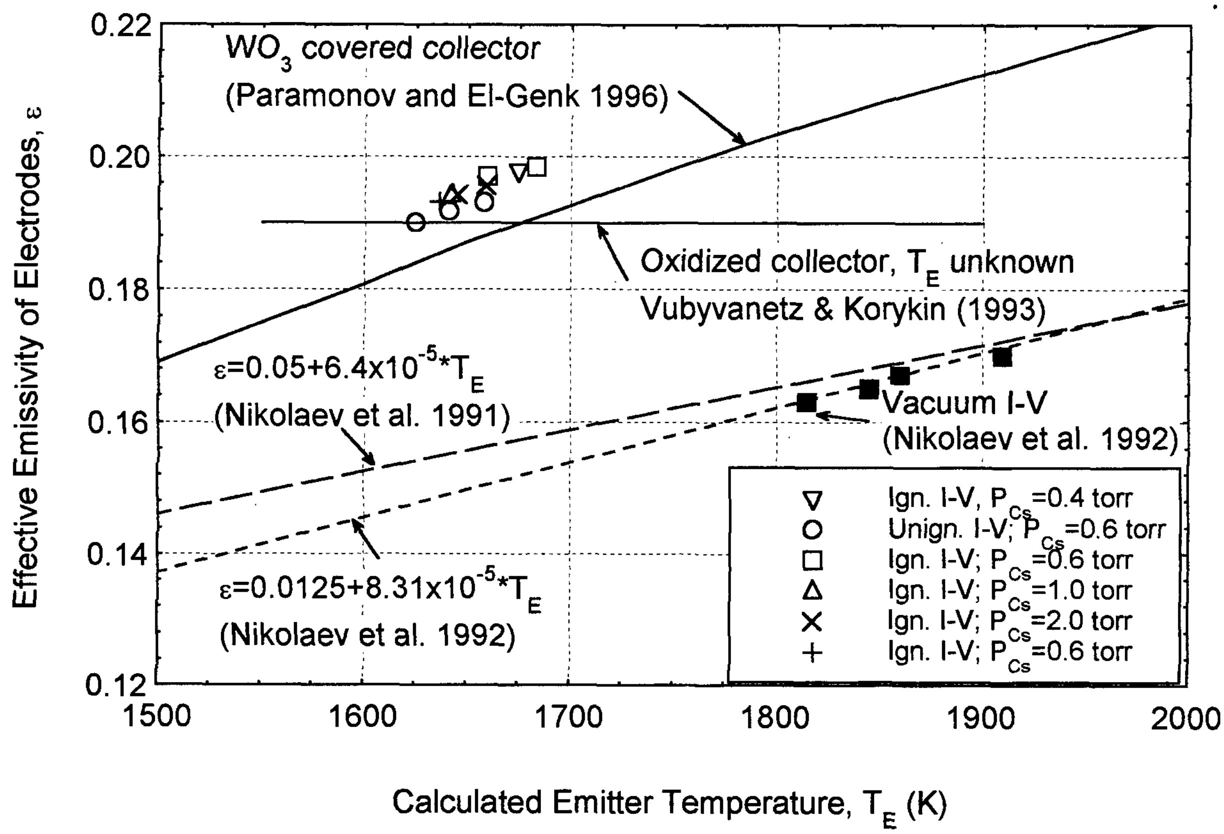


Figure 90. Estimated effective emissivity of Ya-21U TFE electrodes.

As Figure 91 indicates, the optimum output power of Ya-21U decreased ~7% (from 2.98 to 2.77kWe) during more than 2,800 hr of testing in the U.S. (tests #1-#11). This decrease in optimum load power was significantly less than that observed at a constant cesium pressure setting of 0.6 torr and a load voltage of 28-29V (from 2.8 to 2.18 kWe or 22%, as indicated by Figure 87.)

6.6.7.5 Performance of Ya-21U's Thermionic Fuel Elements

The average performance for the 34 work section TFEs was represented by the load voltage and load electric output power. Ya-21U test results revealed that the contribution of individual TFEs was not identical. Variances in performance among work section TFEs were attributed to the following causes:

- Variances in manufacturing processes which resulted in different values of the electrode work functions, the effective emissivity, and the gap size (Nicolaev #38);
- Variances in thermal power input caused by differences in the performance of the TISA heaters and in the electric power input to the individual TFEs;

Variances in the effects of external parameters such as the penetration of contaminants and/or effects of the vibration and shock tests.

The relative performance of Ya-21U work section TFEs at a TISA input power of ~ 84.8-85.6 kW, a load voltage of 27-29 V, and a cesium pressure setting of 0.6 torr is illustrated by Figure 92. The six different tests (a. through f.) illustrated in Figure 92 were performed before and after major events could cause structural changes in the TFEs. The relative performance of each TFE is provided as the ratio of measured load voltage of a particular TFE to the average load voltage of all work section TFEs. Because all work section TFEs are connected in series, their particular voltage ratio represents the relative contribution of each TFE to Ya-21U's electric power output.

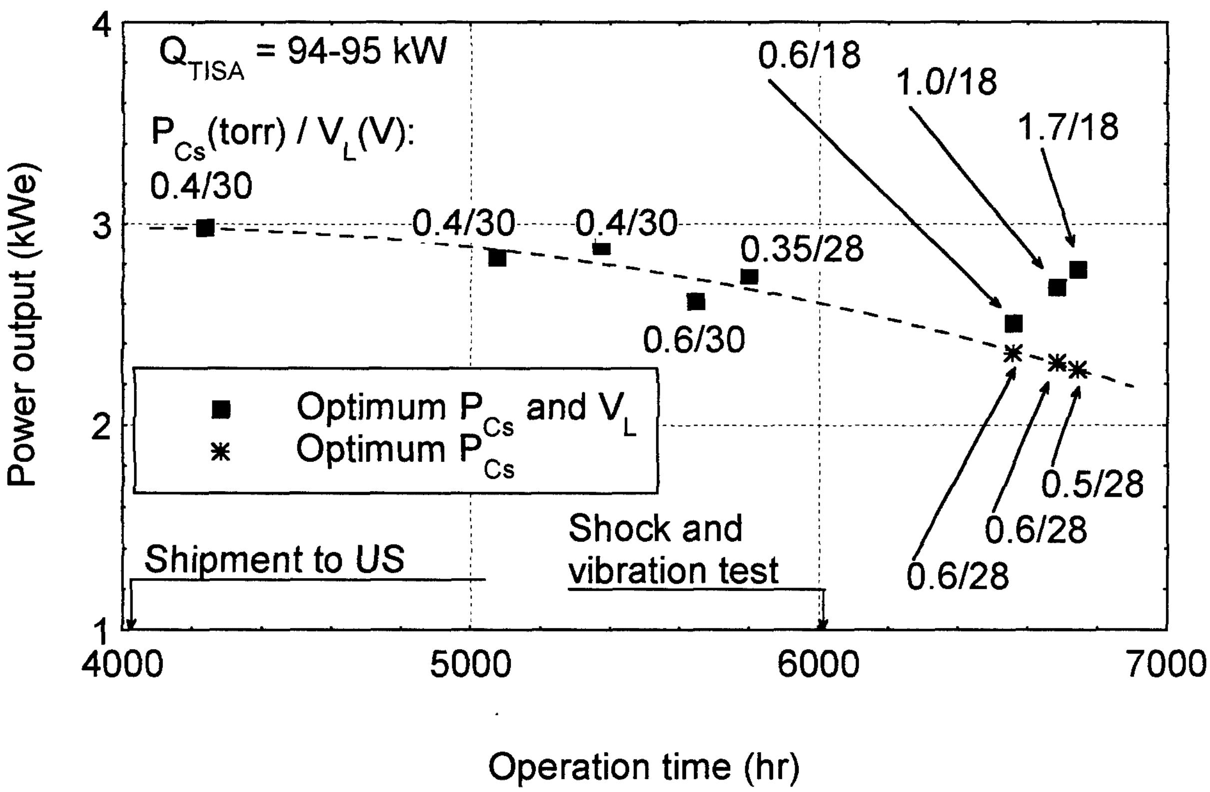


Figure 91. Ya-21U performance at optimum cesium pressure and work section voltage for TISA power input of 95 kW.

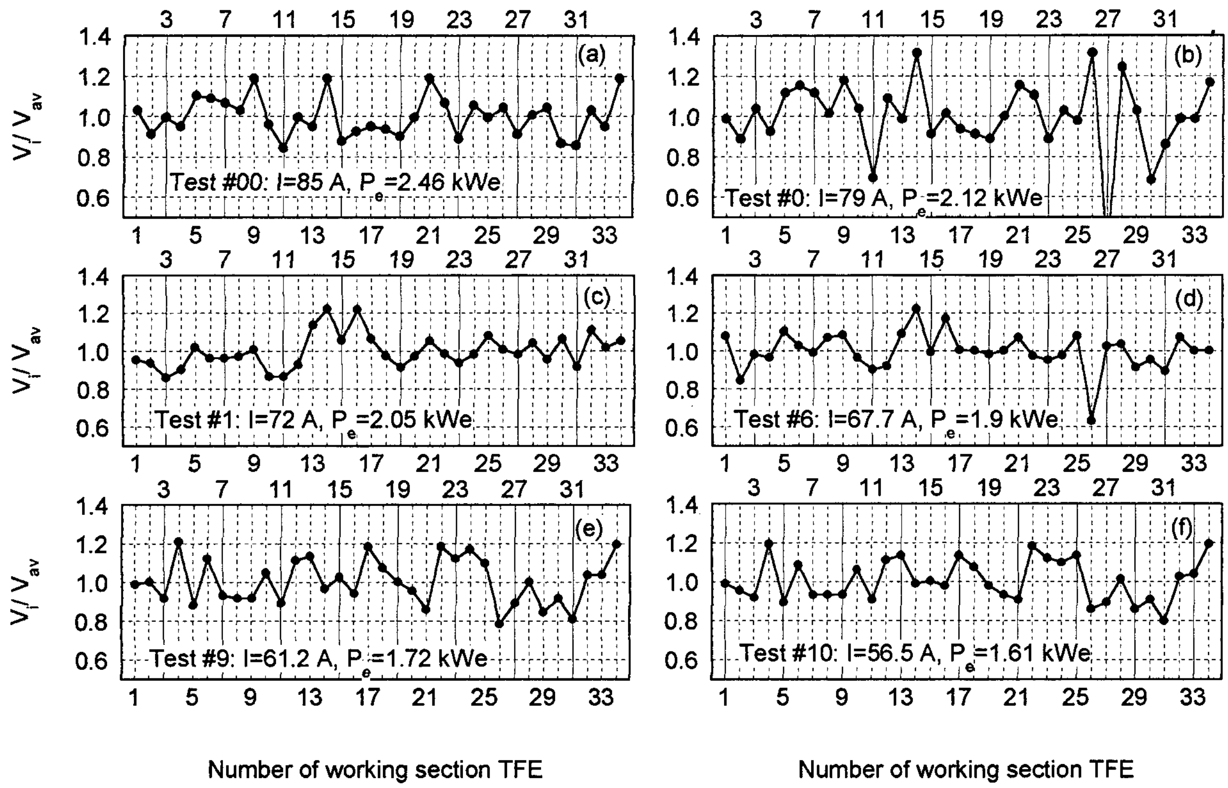


Figure 92. Relative performance of Ya-21U work section TFEs.

Figure 92a indicates there was a +/- 20% variation in performance of individual TFEs during the first Russian test which was caused by the variance in the manufacturing processes. After the high power test in Russia, the variance in individual TFEs increased to +/- 32% although the relative contributions of the individual TFEs changed only slightly, as indicated by Figure 92b. During U.S. test #1, the variance in performance of the individual TFEs decreased back to ~20%, as indicated by Figure 92c. Figures 92c and 92d indicate that the relative contribution of the individual TFEs to the total Ya-21U power output remained nearly the same during tests #1-#8 (~2,000 hr of operation). Thus, the effects of air incursion during this test period appeared to be uniform among all working section TFEs. <u>Note</u>: The low voltage of TFE #26 indicated in Figure 92d was caused by a malfunction of measurement equipment.

After the vibration and shock tests, the relative contribution of each individual TFE to the total Ya-21U power output continued to vary randomly within +/-20% as the total power output decreased. This trend was consistent during the remainder of the testing effort and the performance of all TFEs decreased gracefully by almost the same magnitude. No single TFE failed or was damaged severely during the entire test history!

- The electrical power provided by the individual work section TFEs during the Russian tests of Ya-21U and U.S. tests #1, 6, 8, 9, and 10 is indicated by Figures 93a, 93b, 93c, and 93d. The test parameters were nearly the same; TISA power input ~85-86 kW, load voltage ~28-29 V, and cesium vapor setting 0.6 torr.

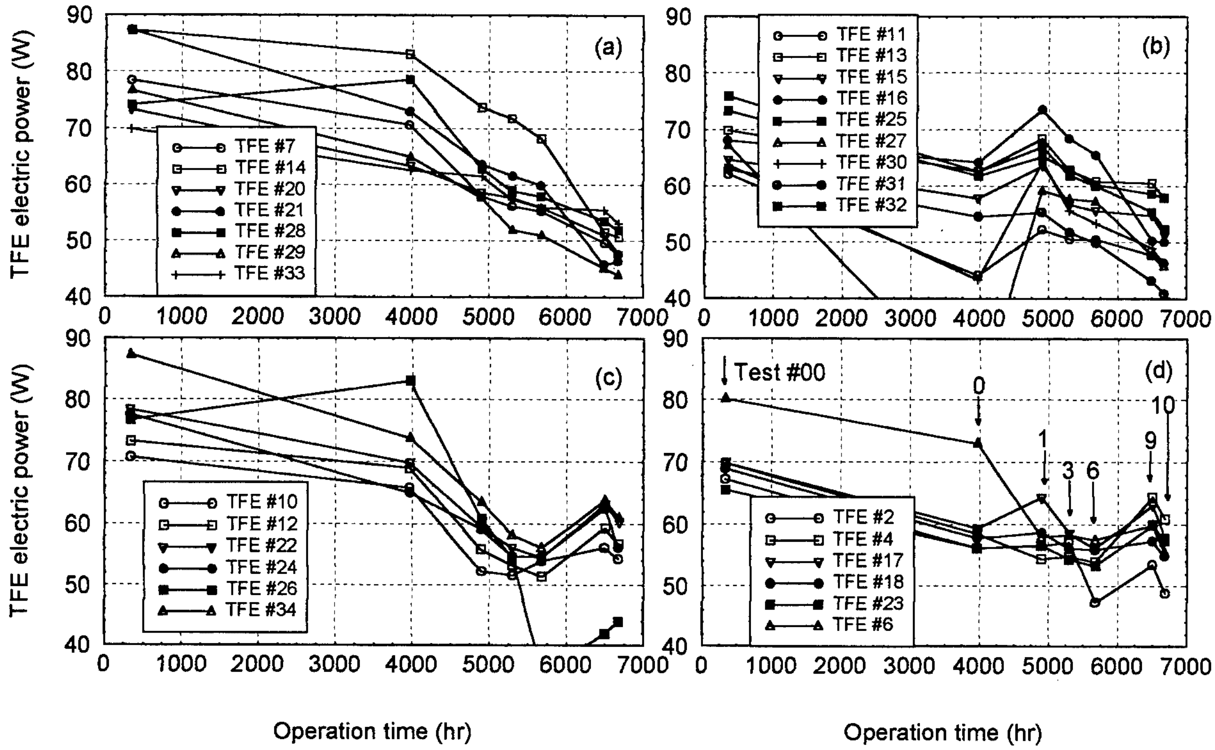


Figure 93. Electrical power generated by individual TFEs of Ya-21U work section.

For TFE performance analysis purposes, the data were divided into five sets, as follows:

- Set 1: TFE performance decrease during Ya-21U's entire test history,
- Set 2: TFE performance increased temporarily after Ya-21U shipment to the U.S.,
- Set 3: TFE performance increased temporarily after Ya-21U vibration and shock test when the cesium system was contaminated by air incursion,
- Set 4: TFE performance increased slightly after shipment to the U.S. and after vibration and shock tests, and
- Set 5: TFE performance increased after U.S. #1 for TFEs #1, 3, 5, 8, 9, and 19.

To gain insight into the performance of Ya-21U's TFEs, V-A characteristics of four different TFEs (#3, 14, 17, and 10) were measured at constant TISA input powers of 80.5 and 90.5 kW and at cesium pressure settings of 0.45 and 0.7 torr, as indicated by Figures 94a, 934. 934, and 94d. The data were collected by proceeding from a high voltage to a low voltage and then from a low voltage to the high voltage. The transition from the unignited to the ignited mode is clearly indicated by the Figures 94a through 94d.

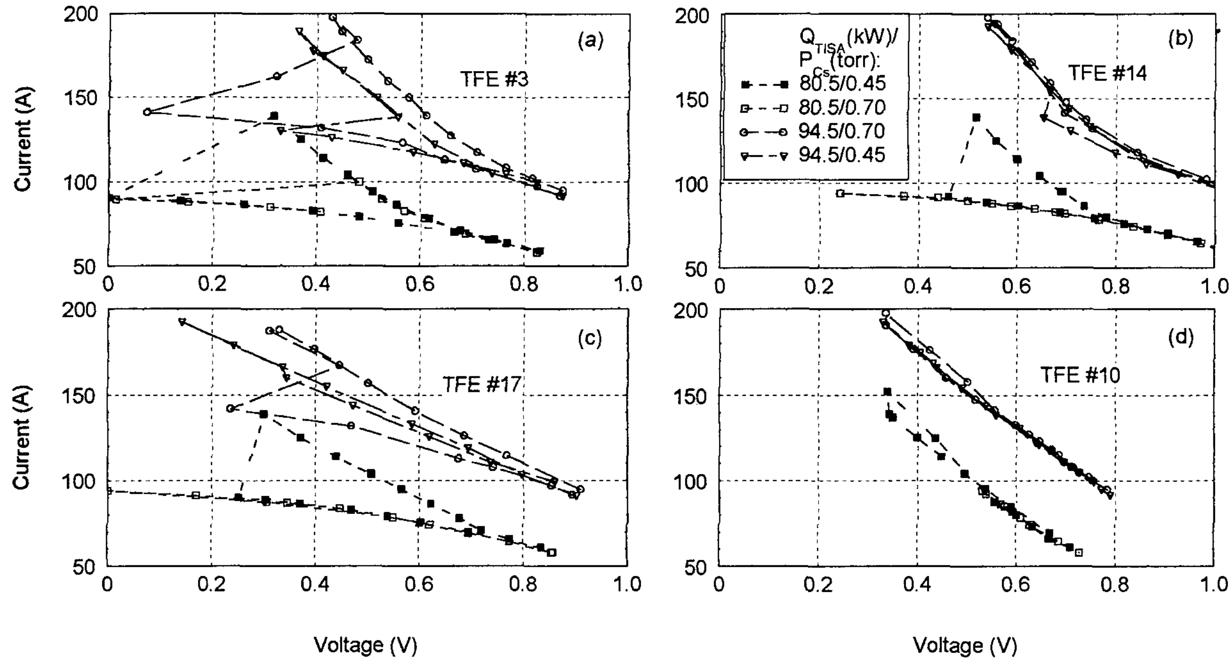


Figure 94. Static volt-ampere characteristics of some work section TFEs in Ya-21U test #3

As indicated by Figure 94a, the V-A characteristics were typical for most working section TFEs and the transition from the unignited mode was observed at different levels of TISA power input and cesium pressure. At the TISA power input of 80.5 kW, changes in the cesium pressure setting has little effect on the measured V-A characteristics. At this power input, Ya-21U's work section current was higher at the 0.45 torr cesium pressure setting than at the 0.7 torr setting because the voltage at the 0.7 torr setting was not was not low enough to cause a transition to the ignited mode, as indicated by Figures 94b and 94c.

As illustrated by Figure 94a, the comparison of the V-A characteristics of TFE #3 at a TISA power input of 94.5 kW indicated the cesium pressure setting was below its optimum setting because for that particular TFE, a higher cesium pressure setting corresponded to a higher current.

The conclusion derived from V-A characteristics, indicated by Figures 94a through 94d, was that at these input power levels and Ya-21U work section voltage of 28-30 V, all TFEs operated in the diffusion mode and were less efficient than in the ignited mode at the lower work section voltage. This conclusion was supported by previous results, illustrated by Figure 95, that indicated a decrease in optimum work section voltage as the cesium pressure setting was increased which then caused the TFEs to operate in the ignited mode.

<u>Note</u>: The transition from the unignited mode to the ignited mode occurred at higher voltages when the TISA input power was increased, as indicated by Figures 94a through 94d. Thus, the work section TFEs would operate in the ignited mode, if Ya-21U work section were heated by

nuclear fission at a nominal thermal power level of 115 kW and voltage of 28-30 V. This would correspond to a TISA power input to the TFEs of more than 120 kW.

Examples of V-A characteristics of good and poor performance TFEs are indicated by Figures 93b and 93c. The V-A characteristics of good performance TFEs in the ignited mode, Figure 93b, had a steeper slope and shifted toward a higher voltage when compared to poor performance TFEs, Figure 93c. The observed results suggested that poor performance of some of Ya-21U's work section TFEs could be caused by the following (Paramonov #40):

- A low bare emitter work function,
- A high emissivity of the electrodes, or
- A high cesiated collector work function.

At a TISA power input of 80.5 kW, the unignited V-A characteristics were similar for the majority of Ya-21U working section TFEs. This indicated that the saturation current was almost constant and equal to ~90-95 A. This suggested the TFEs were operating in the under-compensated mode at this power level at the cesium pressure settings of 0.45 - 0.7 torr. In this mode, saturation current was independent of the emitter work function and depended on the emitter temperature, cesium pressure, and the interelectrode gap dimension (Baksht #41).

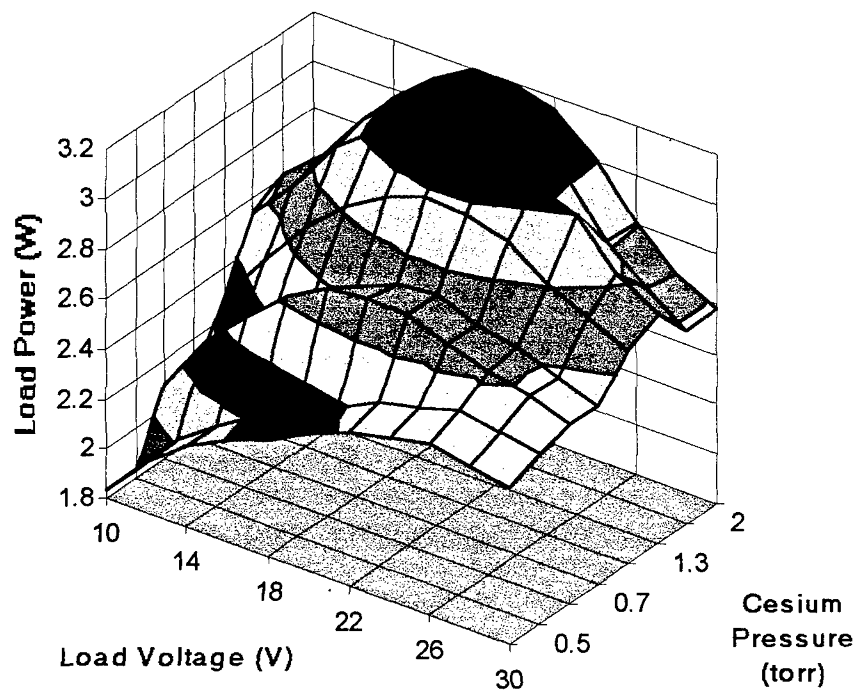


Figure 95. Effect of cesium pressure on optimum work section voltage and output power at TISA power input of 105 kW during Ya-21U test #11.

Because Ya-21U's working section TFEs were all operating at the same cesium pressure, the observed saturation current indicated that all TFEs had approximately the same gap dimension and interelectrode gap thermal resistance.

The causes for the V-A characteristics of some TFEs, indicated by Figure 94d could not be explained. Their V-A characteristics indicated a weak dependence on cesium pressure. The equal slope of V-A characteristics in the ignited mode of TFE #10, Figure 94b, and TFEs #3 and #14, Figures 94a and 94b indicated these TFEs had the same effective work function. The shift of the V-A characteristics of TFE toward a lower voltage suggested that this TFE had a higher collector work function and a lower thermal resistance of the interelectrode gap than TFEs #3 14, and 17.

6.6.7.6 Effects of Thermal Cycling

Ya-21U was operated at a steady-state TISA power input of 105 kW and a cesium pressure setting of 0.6 torr for ~136 hr during test #12 and ~208 hr during test #13. At the beginning of each test, V-A characteristics and work section load resistance determined for the optimum load voltage of ~26V. During the beginning of test #12, a gradual decrease in Ya-21U's output power was observed which diminished toward the end of the test, as indicated by Figure 96. The apparent oscillations in work section voltage and output power had a periodic cycle of 24 hr which were caused by variations in the ambient day and night temperatures. The temperature oscillations affected the actual resistance of the work section circuitry and the calibration of the Baikal test stand equipment. (Paramonov #35)

During test #12, Ya-21U's output power decreased by only 37 W after 136 hr of operation. After shutdown and restart for test #13, Ya-21U's output power never returned to the value observed at the end of test #12. At the beginning of test #13, the V-A characteristics were repeated and the optimum work section load voltage remained unchanged. However, the corresponding current had decreased by ~10 A and resulted in a decrease in output power from 2.29 kW to 2.11 kW, as indicated by Figure 96. Although the work section current remained constant throughout tests #12 and #13, a slight increase in the slope of the V-A characteristic was observed, as indicated by Figure 97. The increase in the slope suggested that the observed increase in Ya-21U's power output could have been caused by either a change in the emitter work function or a change in the actual cesium pressure in the TFEs.

When an optimization of output power related to various cesium pressure settings was attempted at the end of test #13, it was observed that the cesium pressure could not be controlled by the cesium throttle valve. The observed result was a sharp reduction in the actual cesium pressure had occurred within the TFEs. Thereafter, the cesium throttle valve was fully closed to a calibrated setting of ~4.5 torr and the V-A characteristics determined, as indicated by Figure 97.

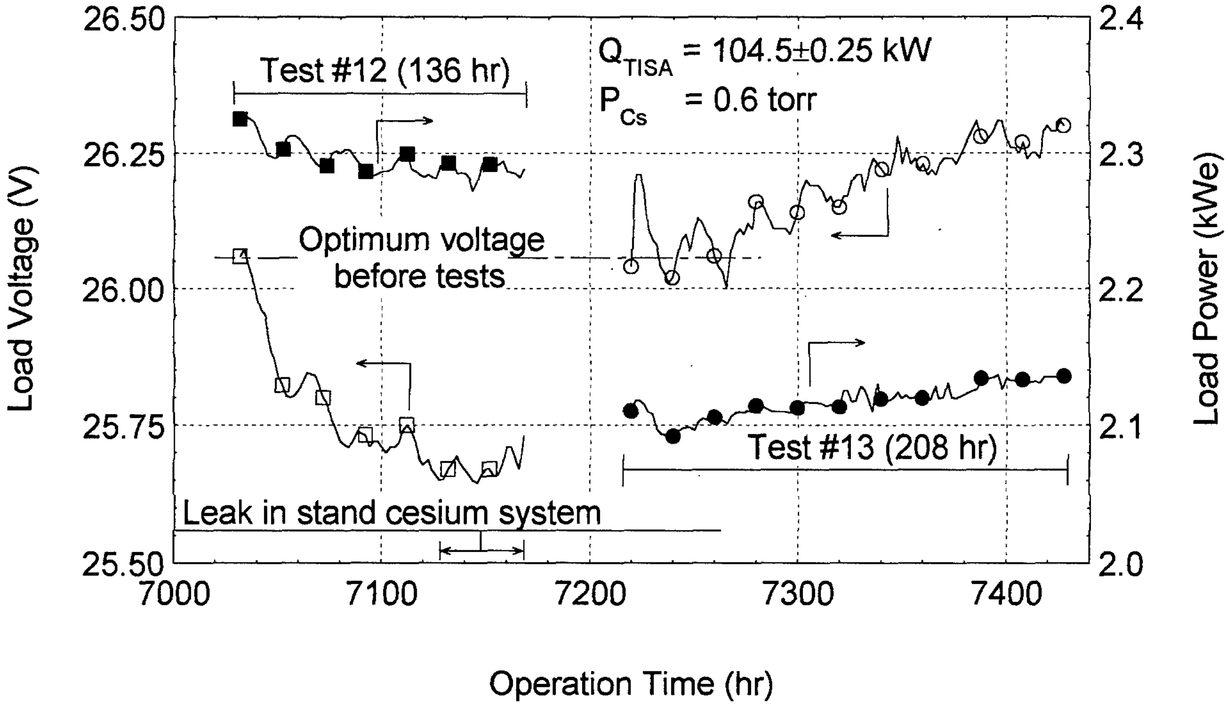


Figure 96. Ya-21U work section voltage and power output during tests #12 and #13.

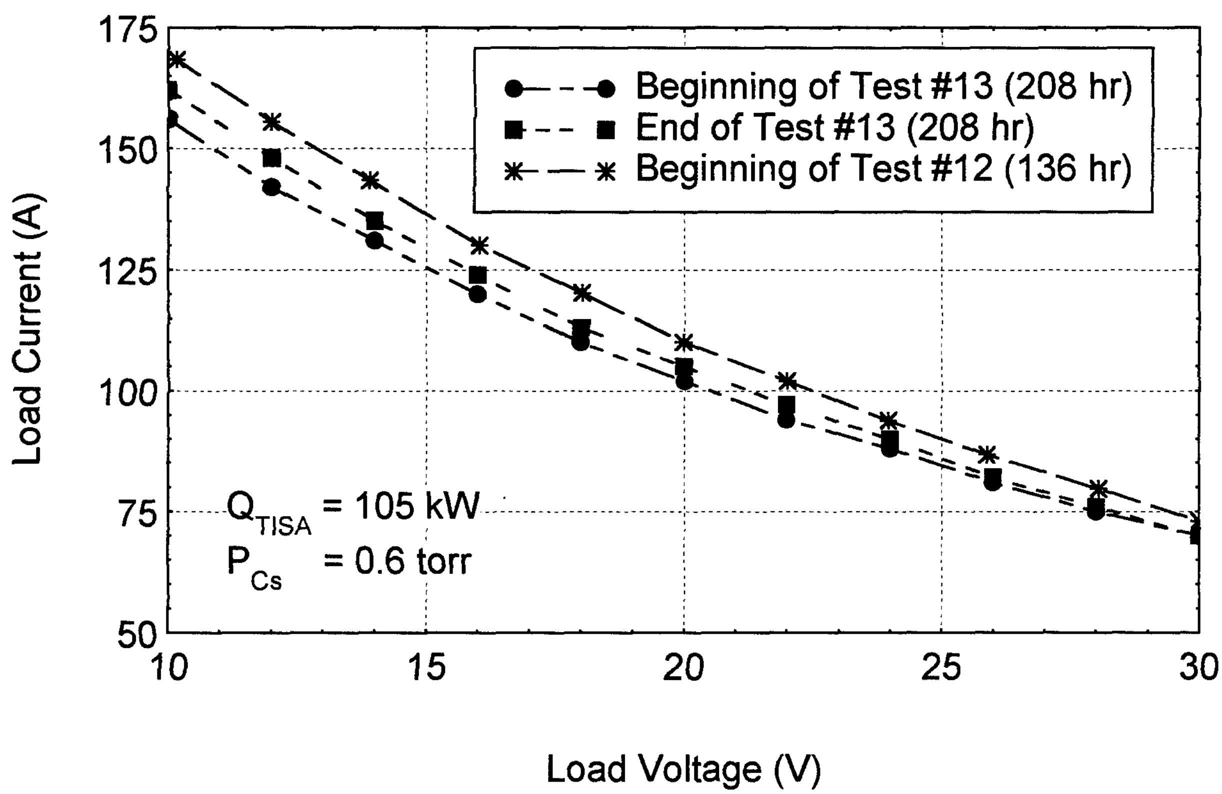


Figure 97. Volt-ampere characteristics of Ya-21U work section during tests #12 and #13.

At the conclusion of test #13, the observed slope of the V-A characteristic at a TISA input power of 105 kW and decrease in the output power of Ya-21U indicated the actual cesium pressure in the TFEs to be significantly below the optimum pressure, as illustrated by Figure 98. A significant increase in leakage of cesium vapor from the cesium supply system had occurred.

Minor leaks of cesium vapor from the cesium system that increased thereafter during tests #9 through #12 were caused by the vibration and shock tests and number of thermal cycles had now become major leaks and were responsible for observed changes in Ya-21U's performance.

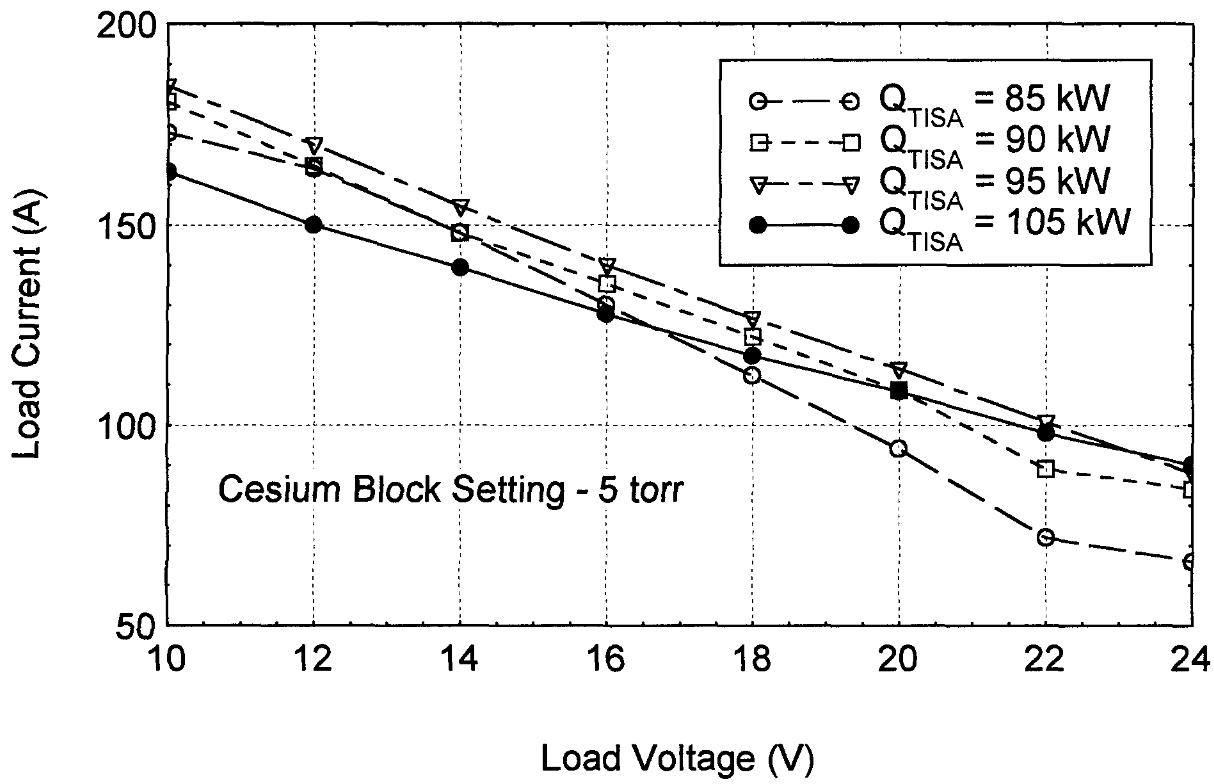


Figure 98. Volt-ampere characteristics of Ya-21U work section at end of test #13.

6.6.8 <u>Reflections and Recommendations</u>

The following reflections and recommendations are presented for consideration during future thermionic system technology assessments, development, and demonstration programs. The Ya-21U system test program, test sequence, and test conditions were more extensive, more stressful, and more damaging than the system was designed to undergo and withstand during the normal factory through orbital operation life cycle. Accordingly, the thermionic system evaluation tests resulted in performance changes that were not representative of expected performance during nominal operation. For example:

- Vibration and shock tests were performed on the system after the system had operated for more than 6,000 hr and had completed 17 thermal cycles. The cumulative effect of the vibration and shock tests exceeded several times what a TOPAZ-II system would have experienced during acceptance testing, ground handling, and transportation prior to launch into orbit.

- During launch, the structure, reactor, TFEs, and other major components would not have experienced the 30 min sine and random vibration sweeps that permitted force amplifications and number of cycles to severely exceed qualification test limits. For example: the extended vibration sweeps and excessive forces on the cesium block of the cesium supply system that caused a failure of a seal weld on the cesium vapor vent line to space and permitted air to contaminate the cesium block and throttle valve would not have occurred during a launch into space.

- During operation in space, the major source of contamination of TFEs would have been oxygen that would have diffused from the nuclear fuel. If TFE leaks had occurred during operation in space, air from the test facility would not have penetrated the cesium supply system.

  If leaks in TFEs and/or cesium vapor supply system would have occurred in space, the effects would not appear as the transport of emitter materials to the collector, a change in work functions of the emitter and collector, or a change in the emissivities of the emitter or collector.

- Likewise, the cesium system throttle valve would not have been cycled hundreds of times throughout its range as occurred during the cesium optimization evaluations and numerous startups and shutdowns. Instead, the throttle valve would have been set during the system acceptance test and remained in that position for the remainder of the system's life.

- Likewise, the entire system would have experienced one rapid startup to the system design power level and would have remained at this power level by adjustment of the reactor control rods throughout the system's useful life. Ya-21U experienced 4 rapid startups, 3 emergency shutdowns, more than 17 thermal cycles from ambient to operating temperatures, and hundreds of input power changes between 70 and 105 kW.

The TOPAZ-II Ya-21U thermionic system evaluation tests are now completed. The resulting technology was transferred by numerous technical papers presented at various symposiums, provided to attendees of technical seminars, and is now available for use by future space mission planners and developers. The following recommendations are provided for consideration during future thermionic technology transfers, power system evaluations, and space power system development:

- Prevent, avoid, or minimize severe emergency shutdowns of thermionic space power systems that are caused by failures, malfunctions, and/or poor maintenance and calibration of thermal vacuum test stands, power supplies, test equipment, and test instrumentation.

Note: Not one emergency shutdown was caused by a failure of a single component of the Ya-21U system during the thermionic system evaluation tests performed in the U.S.

- Provide, install, calibrate, and use redundant sensors to monitor, control, and evaluate the performance and degradation modes of space power systems, subsystems, critical components, system sensors, and controls.

  Note: Performance of the cesium vapor supply and pressure regulation system could not be monitored or evaluated directly during the entire thermal vacuum test sequence because there were no pressure sensors on the cesium supply system.

- Do not, do not perform non-standard mechanical vibration and shock tests at excessive test levels for extended durations on a thermionic space power system after completion of extensive, exhaustive, and rapid startup thermal vacuum test demonstrations.

  Note: The Ya-21U system was designed by Russian engineers to be launched in an inverted orientation (the reactor and much heavier radiation shield were at the bottom). The vibration and shock tests of Ya-21U were performed at the Sandia National Laboratory with the reactor and radiation shield at the top.

  This orientation amplified the input g-levels of the test fixture and caused excessive g-levels to be experienced by the reactor, shield, and other components. The mechanical test preparations, planning, execution, and monitoring were performed by TSET operating personnel who did not anticipate the response of the Ya-21U system to the test conditions.

- Engineering models of the space power system and subsystems must be prepared and used to guide test planning, to provide on-line monitoring of test conditions and results, and to assist performance evaluations.

7.0 BAIKAL TEST STAND EVALUATION

7.1 INTRODUCTION

This section describes and evaluates the main systems and components of the Baikal test stand as they were assembled, installed, and operated in the TSET Laboratory. This equipment was used for non-nuclear testing of the Russian TOPAZ II space power system. (Fairchild #36)

The Baikal test stand was built at the Central Design Bureau for Machine Building (CDBMB) in St. Petersburg, Russia, and was included with the U.S. purchase of the two systems, V-71 and Ya-21U. The Baikal test stand included most of the test equipment required for non-nuclear thermal vacuum testing of Ya-21U. Preparations were completed for its installation in the TSET Laboratory at the New Mexico Engineering Research Institute (NMERI) prior to delivery.

After purchase of the systems and equipment, the Baikal test stand was disassembled, crated, and delivered, along with two TOPAS II systems, by two C-5A Air Force cargo planes to Albuquerque, NM. After unloading, the systems and equipment were placed in interim storage at Kirtland AFB. Re-assembly of the Baikal test stand began in June 1992 and was completed in October 1992. Operational checkout and testing began shortly thereafter.

The main vacuum system consisted of two mechanical roughing pumps, two 10,000 l-torr/s turbomolecular pumps (TMP), a large vacuum chamber, and associated valves, cold traps, and various instrumentation. The vacuum chamber was approximately 9 ft in diameter and 20 ft tall. The chamber was supported on a test stand structure located in a 15-ft deep pit. Sections of the vacuum chamber were bolted together and had tongue and groove interfaces that contained gaskets to form a leak-tight seal. The upper section had a vacuum-tight mechanical linkage to adjust the cesium vapor pressure in the TFE interelectrode gaps. The upper section contained electrical feed-throughs to supply power to TISA heaters and auxiliary power to the NaK EM pump. Many feedthroughs were located in the bottom section and included the following: electrical control, instrumentation signals, working section output power, cooling water piping, NaK fill and drain, and a cesium system vapor discharge and evacuation line.

The two Russian-built 10,000 l-torr/s TMPs provided the high volume and low pressure capacity required for high temperature, thermal vacuum testing of Ya-21U. Liquid nitrogen-cooled cold traps were located downstream of the TMPs and were used to trap and keep back-streaming oil or contaminants from entering the vacuum chamber. The vacuum chamber and vacuum system had numerous connections for vacuum gauges and other instrumentation. Most of the vacuum gauges had thermocouple type sensors and were used during startup of vacuum systems and monitoring of mechanical fore-vacuum piping and pumps. Cold cathode sensors were used for monitoring of the high vacuum system pressure.

Mass spectrometers and leak detectors were used on the main vacuum system. Leak detector fittings were located at cold traps to check for vacuum chamber leaks after re-assembly. A mass spectrometer was connected to the vacuum chamber to monitor contaminants during operation.

The cesium evacuation system evacuated the interelectrode gaps of the TFEs, collected and condensed cesium vapor discharged from Ya-21U during test operation, and enabled back-filling of the interelectrode gaps with helium during system shutdown. A mass spectrometer was connected to the cesium evacuation system to detect contaminants, if any, and monitored contaminant levels during operation.

The load bank controlled the output voltage and dissipated the power produced by Ya-21U during operation. The load bank was located near the Baikal test stand vacuum chamber on the main floor of the TSET lab high bay.

A re-circulating cooling water system was used to cool the Baikal test stand vacuum pumping systems, vacuum chamber, selected vacuum feedthroughs, instrumentation and control drives, and other test stands within the TSET facility.

When Ya-21U was operating, an interruption of electrical power for more than 2 s would cause rapid cooling, severe thermal shock, and high thermal stresses on critical TFE and reactor components. This could significantly degrade performance and life expectancy of the system. An uninterruptable power supply (UPS) system provided 50 Hz, 380 VAC electrical power for operation of the Russian-built equipment during such unforeseen losses of commercial facility power.

Modifications of the Baikal test stand to accommodate testing preparations prior to the final thermal vacuum system tests of Ya-21U were described in previous sections of this report.

Very few equipment failures of the Baikal test stand occurred during the first thermal vacuum tests and problems with test equipment were fewer than expected for the extended operations and test cycles. The vacuum system maintained its integrity during the entire test period. Russian sensors and instruments operated normally, required only basic maintenance to keep them calibrated, and contributed to the overall low operating and maintenance cost of the Baikal test stand.

The highly trained Russian and U.S. specialists and durability of Russian equipment contributed significantly to the successful system test program and transfer of Russian thermionic space power technology.

7.2 VACUUM SYSTEM

The main vacuum system of the Baikal test stand, as illustrated by Figure 99, consisted of two mechanical roughing pumps, two 10,000 l-torr/sec turbomolecular pumps, a large vacuum chamber, and associated valves, cold traps, and instrumentation. The main vacuum system evacuates the vacuum chamber to a pressure less than 5×10^{-5} torr during testing of the systems. Normal operating pressure during testing was between 10^{-6} and 10^{-7} torr.

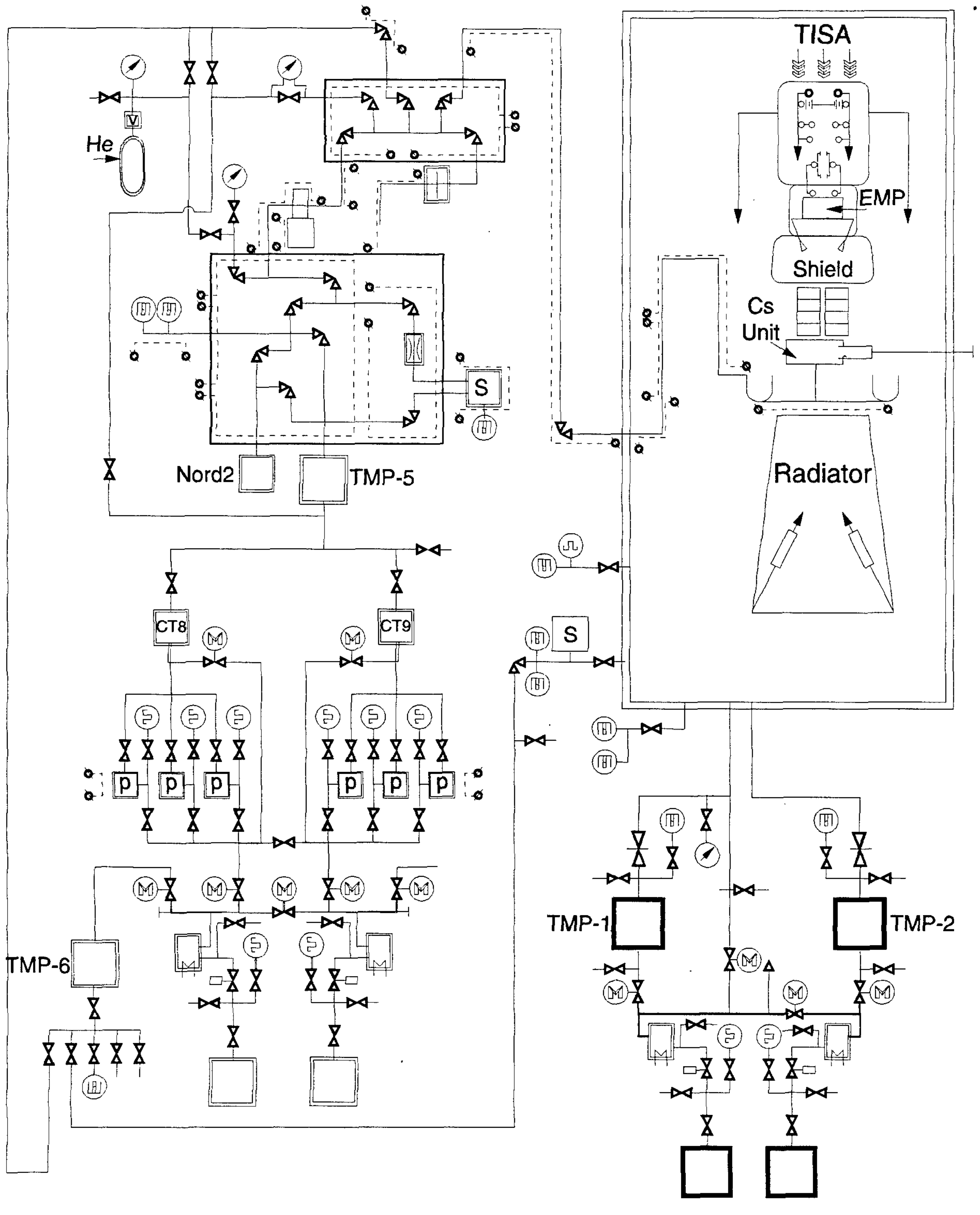


Figure 99. Baikal test stand main vacuum system.

7.2.1 Vacuum Chamber

The vacuum chamber was approximately 9 ft (3 m) in diameter and 20 ft (6 m) tall. The chamber was supported on the test stand structure located in a 15-ft deep pit. The vacuum chamber and support systems were installed in a pit to provide sufficient overhead crane hook height to enable installation and removal of Ya-21U. The chamber consisted of four separate cylindrical sections and a lid that were disassembled to ease installation of the systems, equipment, and instrumentation. The vacuum chamber was constructed of stainless steel and the inner surface was coated with a black enamel to increase heat absorption from the system during thermal vacuum testing at operating temperatures.

The vacuum chamber sections were constructed with external cooling jackets. Water was pumped through the jackets to remove the absorbed heat during test operations. Water entered at the bottom base section, flowed in a single pass up through each section, and exited from the top lid.

Separate water coolant was provided to selected vacuum chamber feedthroughs to cool the system control drum drive motor, pressure gauge unit, and interface cable connectors.

The bottom section of the chamber sat on a steel frame structure approximately 7 ft above the pit floor. The structure provided room under the bottom section for other Baikal test stand equipment. Many feedthroughs were located in the bottom section and included electrical control, instrumentation signals, working section output power, cooling water piping, NaK fill and drain, and a cesium discharge line. The system was secured to a fixture located on the bottom of the vacuum chamber. NaK leak detectors were located under Ya-21U.

The vacuum chamber sections were bolted together. The sections had matched tongue-and-groove mating interfaces that contained gaskets to form leak-tight seals. The upper section had a vacuum-tight mechanical linkage, which was used to operate the cesium vapor supply throttle valve for adjustment of the cesium vapor pressure setting for the TFE interelectrode gaps. Various blank flanges were also provided to install other test fixtures or apparatus in the vacuum chamber. The upper section contained electrical feed-throughs to supply power to TISA heaters and auxiliary power to the NaK EM pump.

7.2.2 Turbomolecular Pumps and Associated Equipment

The two Russian-built 10,000 l-torr/sec TMPs provided the high volume and low pressure required for high temperature, thermal vacuum testing of the TOPAZ II systems. The TMPs required 50-Hz, three-phase power, and frequency converter control units that were located in the control room. The TMPs had an operating speed of 8800 rpm and could evacuate the vacuum chamber from a starting pressure of 5×10^{-2} to 5×10^{-5} torr within a day. Each TMP could be isolated from the vacuum chamber by a motor-operated gate valve. The TMPs were operated together until steady-state conditions were reached after startup of Ya-21U. After

achieving a steady-state vacuum pressure below 10^{-6} torr, one TMP continued operation and the other was kept on standby.

The large double-disc, vacuum gate valves were designed to relieve an over-pressure of the vacuum chamber to the downstream mechanical fore-vacuum pumps. The gate valve actuator drive motors were operated from the vacuum control panel in the control room. During a loss of all 50 Hz electrical power, the gate valves could be manually operated by a hand-wheel on the drive motor assembly.

Liquid nitrogen-cooled cold traps were located downstream of the TMPs and were used to trap and keep back-streaming oil or contaminants from entering the vacuum chamber. The cold traps could be isolated from the vacuum system, disassembled, and cleaned. Each cold trap had connections for a leak detector to permit leak checks before return of the cold trap to service.

Two mechanical fore-vacuum pumps were used to evacuate the vacuum chamber and TMPs. The fore-vacuum pumps could be operated to evacuate the vacuum piping to the vacuum chamber gate valves. A bypass line allowed evacuation of the vacuum chamber at the same time. If the fore-vacuum pumps stop operating, centrifugal switches on the pumps automatically shut electromagnetic valves to isolate the pumps from the vacuum chamber. This design prevented the loss of vacuum and potential contamination of the vacuum chamber and Ya-21U whenever the mechanical fore-vacuum pumps stopped turning. The main vacuum system was designed to permit evacuation of either TMP by either mechanical fore-vacuum pump.

7.2.3 Main Vacuum System Instrumentation

The vacuum chamber and vacuum system had numerous connections for vacuum gauges and other instrumentation. Most of the vacuum gauges had thermocouple type sensors and were used during startup of vacuum systems and monitoring of the mechanical fore-vacuum piping and pumps. Cold cathode sensors were used for monitoring of the high vacuum system, TMPs, and vacuum chamber. Russian-made gauges were used to monitor pressures of the roughing pumps, TMP inlet ducts, and vacuum chamber. The pressure data were obtained from instruments mounted locally and were provided as voltage or current indications that required conversion to vacuum system pressure by using conversion tables. Raw pressure data were provided on meters in the control room and required conversion to vacuum system pressure by the DAS. U.S.-made gauges were also installed on the vacuum chamber and read out in actual pressure on meters mounted locally.

Mass spectrometers and leak detectors were used on the main vacuum system. Leak detector fittings were located at cold traps to check for vacuum chamber leaks after re-assembly. A Russian-made mass spectrometer was connected to the vacuum chamber to monitor contaminants during operation. An U.S. mass spectrometer was also connected to the vacuum chamber for the same purpose. Duplicate instruments were connected to the main vacuum system for comparison of Russian and U.S. data and equipment.

7.3 AUXILIARY VACUUM SYSTEMS

Auxiliary vacuum systems included 500 l-torr/s TMPs, ion pumps, zeolite pumps, mechanical roughing pumps, and associated valves, cold traps, and instrumentation. The auxiliary vacuum system was used by the cesium evacuation system and mass spectrometers. The cesium evacuation system included a 500 l-torr/s TMP, an ion pump, a zeolite pump system, cold traps, mechanical roughing pumps, and associated valves and instrumentation. The equipment and instrumentation were similar to those on the main vacuum system.

Zeolite pumps were added to the cesium evacuation system for initial evacuation of the 500 l-torr/s TMP. Zeolite pumps used activated charcoal for adsorption of condensable gases within the cesium evacuation system, which eliminated potential oil contamination of the Ya-21U cesium system caused by back-streaming from mechanical roughing pumps.

7.4 CESIUM EVACUATION SYSTEM

The cesium evacuation system, as indicated by Figure 100, evacuated the interelectrode gaps of the TFEs, collected and condensed cesium vapor discharged from Ya-21U during test operation, and enabled back-filling of the interelectrode gaps with helium during Ya-21U shutdown. The cesium evacuation system was evacuated by a 500 l-torr/s TMP or an ion pump. During Ya-21U performance tests, operating pressures of the cesium evacuation system were maintained between 10^{-6} and 5×10^{-8} torr.

The cesium vapor, supplied to TFEs by the Ya-21U cesium block, increased the TFE efficiency. During orbital startup simulation and operation of Ya-21U, approximately 0.5 g/day of cesium was vented directly to the cesium evacuation system of the Baikal test stand. During thermal vacuum performance tests in the Baikal test stand, the cesium vapor was collected, condensed, and retained in the cesium evacuation system reservoir.

The cesium evacuation system was connected to the Ya-21U cesium discharge line during system performance testing. The cesium evacuation system was constructed of stainless steel and was heated by electric heaters. Temperatures of various zones were controlled by adjusting each zone's heater current from a panel in the control room. Temperatures were measured by thermocouples and displayed in the control room by strip chart recorders and computer DAS. A temperature gradient was maintained between the high temperature of Ya-21U, cooler cesium evacuation system, and water-cooled reservoir where the cesium vapor was condensed and collected.

Major components of the cesium evacuation system were located under the vacuum chamber on the floor of the pit. The cesium evacuation system contained many valves constructed specifically for this application. The stainless steel knife edges of the valves were seated on the surface of a copper disc. When the valve was shut, the knife edge cut a new seat on the copper disc. A built-in, torque-limiting device ratchets when sufficient torque was applied to seat the valve.

One failure of this type of valve occurred when a crack developed in a welded joint. The subsequent air leak was repaired in-place by re-welding the joint and the valve was returned to service.

After shutdown of Ya-21U, the cesium evacuation system was used to back-fill the TFEs with helium that was purified previously by exposure to heated cesium contained in a separate reservoir. The cesium vapor within the reservoir reacts with any contaminants contained in the helium gas supply. During helium back-filling, pressure was monitored by a pressure gauge located on the system. A Russian mass spectrometer, connected to the cesium evacuation system, was used to determine helium gas purity and to identify and determine levels of contaminants in the gases evacuated from the TFEs.

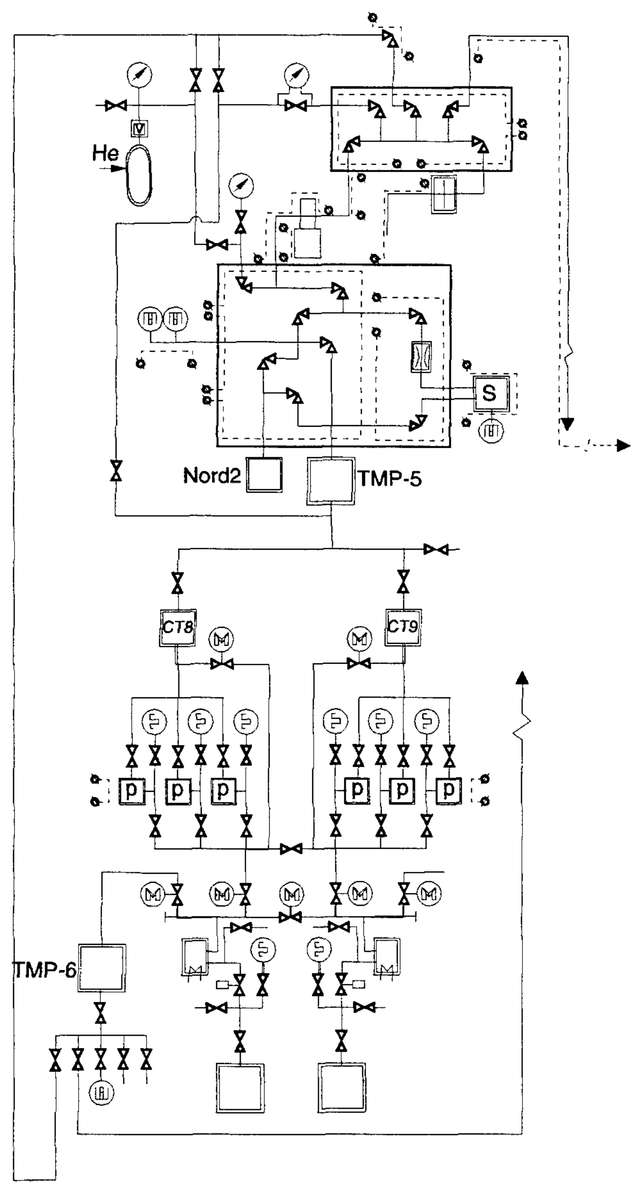


Figure 100. Cesium evacuation system.

7.5 COOLING WATER SYSTEM

The TSET re-circulating cooling water system, illustrated by Figure 101, was used to cool the Baikal test stand vacuum pumping systems, vacuum chamber, selected vacuum feedthroughs, Ya-21U system instrumentation and control drives, and other test stands within the TSET lab. The cooling water system was installed before arrival of the TOPAZ II systems and Baikal test stand. The system used standard 60-Hz electrical power and included two 100-gpm water pumps connected in parallel, cooling tower, sump tank, valves, required piping, and a chemical treatment system to control pipe corrosion and prevent biological growth and contamination.

The water pumps were controlled from a panel in the control room. System pressures and flow rates were monitored at the same panel. The system was designed to supply cooling water from the municipal water supply system, if a power loss of 60 Hz occurred. If power was lost, two solenoid valves would open to bypass the water pumps and cooling tower system.

7.6 UNINTERRUPTABLE 50-HZ POWER SUPPLY

The uninterruptable power supply (UPS) system, illustrated by Figure 102, provided 50 Hz, 380 VAC electrical power for operation of the Russian built equipment. The UPS system included a storage battery system, motor generator, and an emergency diesel generator. When Ya-21U was operating at design operating temperatures, an interruption and loss of all 50 Hz of electrical power for more than 2 s would cause rapid cooling, severe thermal shock, and high thermal stresses on critical TFE and reactor components and could significantly degrade performance and life expectancy of Ya-21U while undergoing performance evaluations. The UPS system was designed to prevent such short duration test interruptions caused by an unexpected loss of utility power.

7.6.1 UPS / Motor Generator System

The UPS battery and control system monitored input power received from the electrical utility power grid. The control system rectified incoming AC power to DC power and applied this power to a bank of backup batteries. The batteries were kept fully charged using this power. When required, the DC power was converted back to three-phase AC power in a static inverter assembly. This AC power was provided to the 60-Hz synchronous drive motor of the motor-generator set. Controls for starting, securing, and stopping the UPS motor generator set were located in the main control panel in an auxiliary room. The auxiliary room also contained the storage batteries and switch gear.

The 60-Hz AC drive motor was coupled by a reduction gear box to the AC generator, which produced the 50-Hz, 380-volt, three-phase, AC power for the Russian-made equipment. The motor-generator set was rated to provide 250 kWe of power to the 380-V bus. On a loss of utility power, the battery bank would provide 5 min of backup power to the fully loaded motor-generator set. During this 5 min (or shorter) period of time, the diesel-generator power supply was started and operated to provide backup emergency power for the 50-Hz equipment.

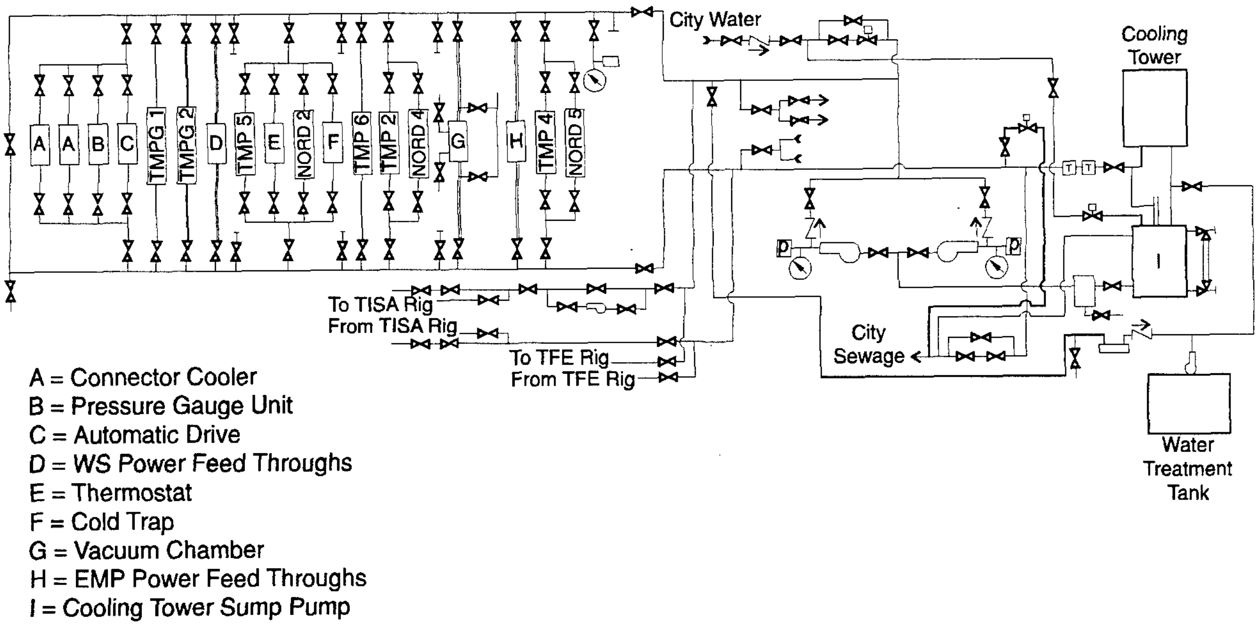


Figure 101. TSET re-circulating water system

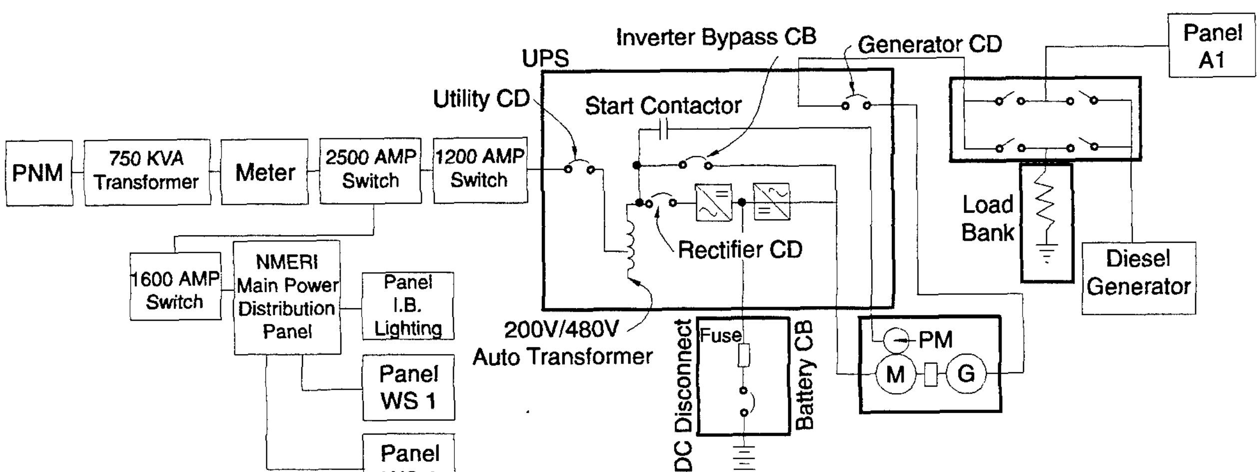


Figure 102. Uninterruptable power supply system.

7.6.2 Emergency Diesel Generator

A 50-Hz, 380-volt, 300-kW diesel generator was installed to provide long-term backup power during a loss of utility power. The diesel was started automatically if utility power was lost for more than 30 s. This feature prevented starting the diesel generator during momentary losses of utility power. The diesel generator was designed to start up and be fully loaded within 10 s after the startup command was given. The diesel generator could also be started manually from the remote UPS control panel located in the control room.

The UPS control room panel permitted the operator to start, operate, and secure the diesel generator; to parallel the motor generator and diesel generator; and to transfer the electrical load to the oncoming generator. Main switch gear breaker positions and buss voltage, current, and power were displayed on the control room panel for the operator. Maintenance and periodic operational testing of the motor generator and diesel generator sets was performed with the available load bank.

7.6.3 Problems Encountered during Thermal Vacuum Tests

The motor generator of the UPS was modified to change the high temperature automatic shutdown feature to a high temperature alarm during operation. This change was made after an unplanned shutdown of the system occurred during test operations of Ya-21U. The unplanned shutdown was caused by the tripping of the high oil temperature switch that was set to trip 20 degrees below the manufacture's stated set point.

7.7 50 HZ POWER DISTRIBUTION

The 50-Hz power distribution system, illustrated by Figure 103, was divided into two main branches: one branch supplied power to the TISA heaters and the other supplied power to all other 50-Hz loads through distribution panels.

7.7.1 Distribution Panel A-3

Distribution Panel A-3 was located in the control room. Power was supplied to A-3 through a breaker in Panel A-1, located in the UPS battery room. Panel A-1 also contained breakers for the variable power transformers for TISA heaters. In the event of an electrical fire, all breakers contained in Panel A-1 could be tripped remotely from the control room.

Panel A-3 contained breakers for all Russian equipment and instrumentation on the Baikal test stand. Power was distributed from this panel to a separate, smaller distribution panel for the TFE test rig.

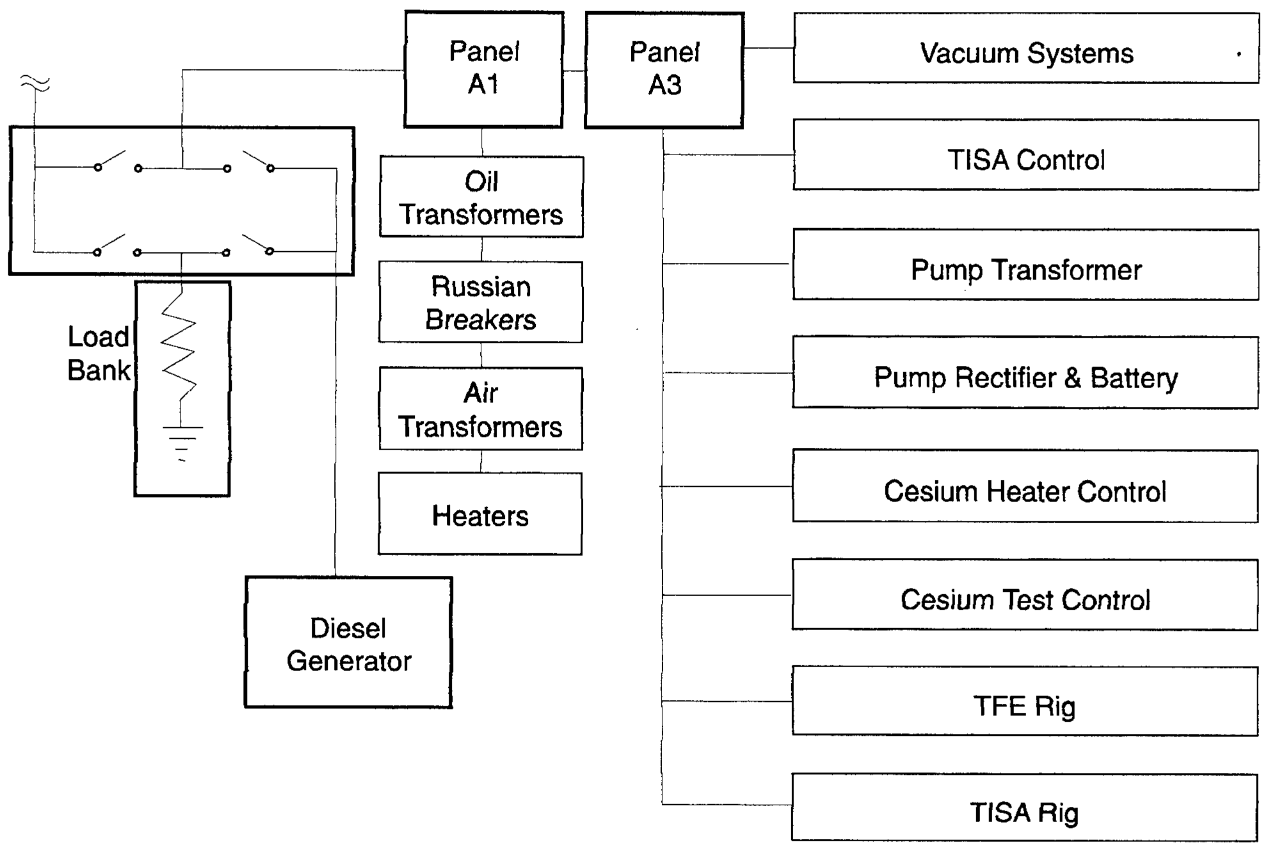


Figure 103. 50-Hz power distribution system.

Power from Panel A-3 was distributed to a variable step-down transformer and rectifier that supplied current to the EM pump of Ya-21U. The amount of current supplied to the EM pump was monitored and controlled by operators in the control room. Another set of step-down transformers, located above the control room, provided 110 VAC power to the cesium evacuation system heaters.

7.7.2 TISA Heater Power

Three breakers in Panel A-1 provided power to three large, oil-filled, variable transformers located in an enclosed bay in the courtyard area. Power from the large variable transformers was supplied to smaller, air-cooled, step-down transformers located on the mezzanine near the Baikal test stand vacuum chamber. These step-down transformers provided low voltage, high current power to the vacuum chamber feedthroughs connected to TISA heaters installed in the Ya-21U TFE cavities.

The output voltage, current, and power of the air-cooled transformers were monitored in the control room. The output from the variable transformers to the TISA heaters was monitored and controlled from a panel in the control room by operators during Ya-21U heatup and steady-state performance testing at operating temperature and during cool-down.

7.8 YA-21U OUTPUT POWER LOAD BANK

The Ya-21U output power load bank, illustrated by Figure 103, included a resistor load bank and a transistor load bank. The load bank controlled the output voltage and dissipated the power produced by Ya-21U during operation. The load bank was located near the Baikal test stand vacuum chamber on the main floor of the TSET laboratory high bay. The transistor load bank had an automatic feature that maintained a constant output voltage and was controlled by operators in the control room. The resistor load bank was controlled by a hand-wheel on the load bank. Output voltage, current, and power levels were displayed on panel meters in the control room.

7.9 TSET LABORATORY EQUIPMENT

The TSET laboratory was prepared prior to arrival of the purchased Russian hardware. The TSET Laboratory included a high bay and low bay work area, control room, and a large outdoor courtyard. The high bay contained a work area for the TOPAZ II systems, Baikal test stand, and miscellaneous support equipment. The low bay contained a TFE test rig and small materials test stands. The control room contained instrumentation and control equipment for operation of Ya-21U, Baikal test stand, and support equipment. The courtyard area contained the UPS equipment, 50-Hz motor-generator, 50-Hz diesel generator, machine shop, liquid nitrogen storage tank, and a pump room for the fore-vacuum and cooling water circulation pumps.

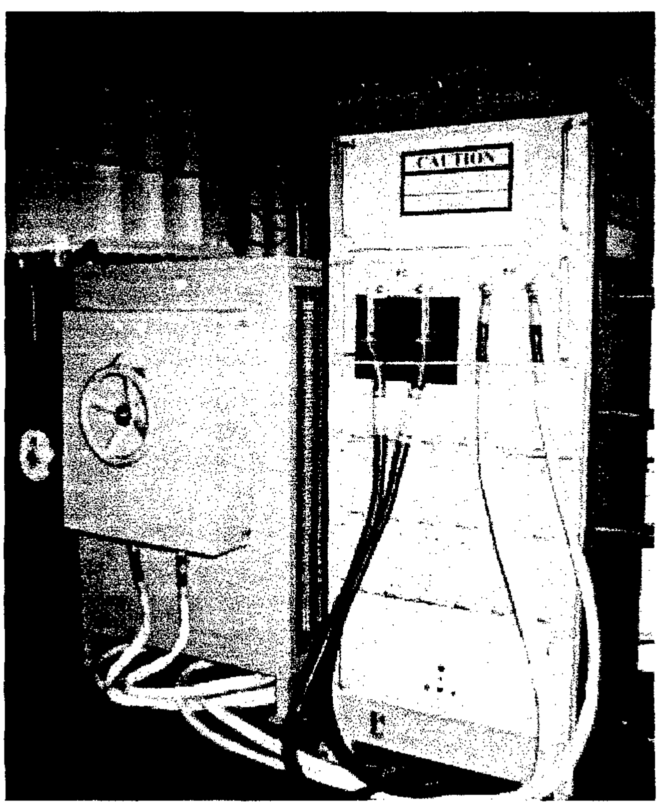


Figure 104. Ya-21U system output power load bank.

Numerous structural changes were made to the laboratory to accommodate the Ya-21U and Baikal test stand. An estimated $400,000 worth of facility preparation costs were saved by using staff engineers and technicians to acquire, refurbish, and install equipment salvaged from SNL and LANL.

The major modifications to the TSET laboratory were completed in November 1991. Facility modifications were continued, as needed, to accommodate changing space power system testing, component testing, and basic thermionic converter research requirements.

7.9.1 Diagnostic System and Equipment

Diagnostic and monitoring requirements for theYa-21U test were provided by chart recorders, indicators, lights, and alarms located in five instrument racks purchased from the Russians. The Baikal test stand working section control panel indicated the electrical output of the Ya-21U TFE working section, controlled the resistive load bank, monitored the TISA heaters, and provided a graphical display of the electric potential of each TFE in the working section.

The TISA instrument rack contained a chart recorder to (1) indicate and record TISA heater power to Ya-21U, reactor outlet coolant temperature, voltage and current for specific groups of TISA heaters; (2) control the power to TISA heaters for the working section TFEs; and (3) provide digital readouts of system power conditions (TISAs heaters and working section output).

Vacuum system recorders and alarms were located on the main instrument rack. This rack also controlled the TISA heaters in the EM pump section. The vacuum instrument rack controlled and indicated status of vacuum system valves and fore-vacuum pumps. A number of pressure indicators were also provided on this panel. The cesium system heater control panel operated and controlled the heat tapes located on various cesium evacuation system lines.

The diagnostic system was connected to sensors by signal and power cables. Interconnecting cables were placed in trenches below the TSET control room floor and connected to terminal blocks in the main terminal cabinet. Signal lines, connected to the terminal blocks, were routed to specific alarms, indicators, and recorders. Certain sensors required and were provided with proper excitation power (voltage or current) within the main terminal cabinet. Terminals for connecting sensor signals to the data acquisition computer interface were also included within the main terminal cabinet.

7.9.2 Data Acquisition System

The DAS for the Baikal test stand, described previously in Section 6, was driven by one 486-66 computer. The system monitors 192 analog channels from the Baikal test stand, and displays and logs to a data file information received during system tests. The conversion algorithms for the data acquisition codes were based on data curves for the Baikal test stand sensors. The DAS data logging rate was selected by the operators and could be 1/min, 1/5 min, 4/hr, or none. Data were stored on the computer hard disk during a period of 24 hr and then transferred automatically at midnight to the main drive on the local area network system by the

communication channel. Several methods for displaying data from the DAS were also available to the operators. The main display panel provides a tabulated view of all calibrated data. Another display provides a graphical schematic of the complete cesium handling system with appropriate data at each sensor location. All of the data being recorded at a time were not displayed. Several other custom displays were also available for operator use.

Once saved, operational data stored by the DAS may be plotted TDAP. TDAP was a data reduction program used by the TOPAZ International Program. The TDAP allows users without computer experience to retrieve sensor data obtained during system tests and to plot numerous combinations of the sensor data. Many of the graphical plots provided in this report were generated by TDAP.

7.10 BAIKAL TEST STAND ASSESSMENT

The Baikal test stand equipment was delivered to Albuquerque, NM, in May 1991 and stored at Kirtland Air Force Base (KAFB). In June 1992, TSET personnel began moving the delivered Baikal test stand equipment to the NMERI facility for re-assembly. Approximately 25 Russians and 12 US engineers and technicians were involved in the transport, assembly, inspection, and testing of over 90 tons of equipment. The entire Baikal test stand was reassembled and tested in less than four months. In October 1992, the first startup and operation of a complete thermionic space power system in the U.S. was accomplished. This startup occurred approximately three months ahead of schedule and under the fixed price budget.

The preparation of equipment when the Baikal test stand was disassembled in St. Petersburg, Russia was an important factor in this accomplishment. Consequently, there were very few equipment failures on the Baikal test stand. The vacuum system has maintained its integrity over the last three years and Russian sensors have operated normally throughout this period. The durability of Russian equipment and highly trained staff contributed to a very successful test program. The Russian Baikal test stand and equipment operated beyond initial expectations and at overall low operating and maintenance cost because Russian maintenance and operations personnel had years of previous experience (mostly military) and provided a successful training program for new U.S. operators of Russian systems.

Russian maintenance and operating personnel had years of previous experience with the equipment and provided a very successful training program on the Ya-21U system and Baikal test stand for the U.S. operators of Russian systems.

The highly trained Russian and U.S. specialists and durability of Russian equipment contributed to the successful Ya-21U test program and transfer of Russian thermionic space power technology.

7.11 LESSONS LEARNED

The Russian specialists expend money and resources only when and where it is required. An example relates to the development of the materials and processes used for the manufacturing of the supporting test equipment - they did not "gold-plate" or use expensive materials when not required to perform the required functions. Accordingly, the majority of the Russian-made vacuum and support equipment was very basic in design, easy to produce, maintain, and inexpensive. Their vacuum and support equipment performed as well as any U.S. equivalent, proved to be very reliable, was rugged, and provided reproducible test environments and test results during the three-year test period.

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ACRONYMS

ACS	Automatic Control System
ADC	Analog-to-Digital Conversion
CDBMB	Central Design Bureau for Machine Building
CR	Customer Representative
DAS	Data Acquisition System
DD	Design Documentation
EM	Electromotive or Electromagnetic
INERTEK	International Energy Technologies
JHU/APL	John Hopkins University, Applied Physics Laboratory
LANL	Los Alamos National Laboratory
MIL-STD	Military Standard
NaK	Sodium (Na) Potassium (K) eutectic liquid metal alloy
NEP	Nuclear Electric Propulsion
NMERI	New Mexico Engineering Research Institute
PC	Permit Card
PSD	Power spectral density
QA	Quality Assurance
REH	Radiator Electric Heater
RTD	Resistance Temperature Detector
RU	Reactor Unit
SNL	Sandia National Laboratory
TC	Thermocouple Temperature Sensor
TCD	Technical Control Division
TD	Technical Document
TDAP	TOPAZ Data Analysis Program
TFE	Thermionic Fuel Element
TIP	TOPAZ International Program
TISA	Thermal Simulators of Apparatus Cores
TMP	Turbomolecular Pump
TOPAZ	Thermionic experiment with conversion in active zone
TSET	Thermionic Systems Evaluation Test
UPS	Uninterruptable Power Supply
V-A	Voltage-Ampere
WMU	Working Medium Unit (Cesium reservoir and control unit)
WS	Working Section (thermionic converter)

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